MINISTRY OF EDUCATION AND SCIENCE OF UKRAINE
NATIONAL AVIATION UNIVERSITY
FACULTY OF AIR NAVIGATION, ELECTRONICS AND TELECOMMUNICATIONS
DEPARTMENT OF AVIONICS

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QUALIFICATION PAPER

(EXPLANATORY NOTES)
FOR THE DEGREE OF «BACHELOR»

SPECIALITY 173 ‘AVIONICS’

Theme: 'Implementation of Terrain-Following Radar in Medium-Haul Aircraft'

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Kyiv 2024

МІНІСТЕРСТВО ОСВІТИ І АУКИ УКРАЇНИ
НАЦІОНАЛЬНИЙ АВІАЦІЙНИЙ УНІВЕРСИТЕТ
ФАКУЛЬТЕТ АЕРОНАВІГАЦІЇ, ЕЛЕКТРОНІКИ ТА ТЕЛЕКОМУНІКАЦІЙ
КАФЕДРА АВІОНІКИ

ДОПУСТИТИ ДО ЗАХИСТУ
Завідувач кафедри
_________Ю.В. Грищенко
«___» ___________2024

КВАЛІФІКАЦІЙНА РОБОТА

(ПОЯСНЮВАЛЬНА ЗАПИСКА)
ВИПУСКНИКА ОСВІТНЬОГО СТУПЕНЯ «БАКАЛАВР»
ЗА СПЕЦІАЛЬНІСТЮ 173 «АВІОНІКА»

Тема: «Впровадження радара слідування за рельєфом місцевості у середньомагістральні літаки»

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Київ 2024

NATIONAL AVIATION UNIVERSITY

Faculty of Air Navigation, Electronics and Telecommunications
Department of avionics
Specialty 173 ‘Avionics’

APPROVED
Head of the department
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‘___’____________2024

TASK

for qualification paper

Illia Vladislavovych Kucherenko

1. Theme: 'Implementation of Terrain-Following Radar in Medium-Haul Aircraft', approved by order 385/ст of the Rector of the National Aviation University of 14 March 2024.

2. Duration of which is from 13 May 2024 to 16 June 2024.

3. Input data of graduation work: Navigation, radar systems, low-altitude, low-altitude maneuvering, terrain-avoidance, terrain-following, autopilot, Terrain-Following Radar

4. Content of explanatory notes: List of conditional terms and abbreviations, Introduction, Chapter 1, Chapter 2, Chapter 3, References, Conclusions.

5. The list of mandatory graphic materials: Figures, charts, graphs.

6. Planned schedule

№	Task	Duration	Signature of supervisor
1.	Validate the rationale of the qualification paper theme	13.05.2024	
2.	Carry out a literature review	15.05.2024	
3.	Develop the first chapter of the qualification paper	22.05.2024	
4.	Develop the second chapter of the qualification paper	29.05.2024	
5.	Develop the third chapter of the qualification paper	05.06.2024	
6.	Tested for anti-plagiarism and obtained a review of the qualification paper	03.06.2024	
7.	Preparation of presentation and report	10.06.2024	

8. Date of assignment: '___ ' ____________ 2024

Supervisor _______________ O.V. Kozhokhina

The task took to perform _______________ I.V. Kucherenko

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ABSTRACT

Explanatory notes to qualification paper 'Implementation of Terrain-Following Radar in Medium-Haul Aircraft' contained 65 pages, 30 figures, and 9 references.

Keywords: AUTOPILOT, LOW-ALTITUDE, LOW-ALTITUDE MANEUVERING, NAVIGATION, RADAR SYSTEMS, TERRAIN-AVOIDANCE, TERRAIN-FOLLOWING, TERRAIN-FOLLOWING RADAR.

The object of the research – The process of implementing terrain-following radar in medium-haul aircraft.

The subject of the research - Implementation of Terrain-Following Radar in Medium-Haul Aircraft.

Purpose of graduation work – Exploring ways to enhance the safety and efficiency of low-altitude flights through the implementation of terrain-following radar in medium-haul aircraft.

Research Method – Calculations, comparative analysis, and processing of literature sources.

Scientific novelty – Proposed methods for improving the safety of low-altitude flights through the innovative use of terrain-following radar in medium-haul aircraft.

CONTENTS

LIST OF ABBREVIATIONS

AA Anti-air

AAD Anti Air Defence

ADI Attitude Director Indicator

AESA Active Electronically Scanned Array

DCLT Declutter

ECM Electronic CounterMeasures

EM Electromagnetic

FLCS Flight Control Systems

FP Flight Path

GM Ground Mapping

HUD Head-Up Display

MFD MultiFunction Display

IEEE Institute of Electrical and Electronics Engineers

LANTIRN Low Altitude Navigation and Targeting Infrared for Night

LCOS Lead Computing Optical Sight

LPI Low Probability of Intercept

NAV navigation

NM Nautical Miles

NVP Navigation Pod

OSB Option Select Button

RADAR RAdio Detection And Ranging

RCS Radar-Cross Section

RF Radio Frequency

SCP Set Clearance Plane

SIT Situation display

SNR Signal-to-Noise Ratio

STBY StandBY

TA Terrain-Avoidance

TAWS Terrain Awareness and Warning System

TF Terrain-following

TFR Terrain-Following Radar

T/R Transmit/Receive

VLC Very Low Clearance

WX Weather

ZCL Zero Command Line

INTRODUCTION

Radio Detection and Ranging technology have significantly developed since its first wide usage in World War II, so much so that five years after World War II have ended, Cornell Aeronautical Laboratory has developed a concept of Terrain-Following (TF) and Terrain-Following Radar (TFR) technology. In 1962, 17 years after the of World War II, English Electric Canberra testbed was the first aircraft to carry TFR. In 1967, General Dynamics F-111A Aardvark was the first mass produced aircraft with TFR on-board. In 1960s and 1970s TFR concept and technology was widely adopted for use in strike aircraft including Panavia Tornado, Sukhoi Su-24 and already mentioned General Dynamics F-111A(B, C, D, E, F, K). Technology was also used in military helicopters such as Sikorsky MH-53J/M Pave Low III.

It also can be used for a civilian purpose. It already used by civilian aircraft that map the ground and wish to maintain a constant height over it and in commercial drones which can mount the system for finding unexploded ordnance and in archaeology. The terrain in many parts of the world is not even, visibility is not always optimal, and pilot skill is not always sufficient - Automatic TF is able to automatically change the pitch angle of the aircraft to avoid collision with the ground and ensure safe maneuvering in the vertical plane. The TFR system provides opportunities to improve flight accuracy in demanding conditions such as low altitudes and limited visibility. The implementation of this system can contribute to the development of new approaches to flight control, which will significantly increase safety, especially under high load conditions during critical maneuvers or when flying in difficult atmospheric conditions. And eventually we will see artificial intelligence partially or fully controlling the aircraft, therefore it will need a means of visually identifying what in the front, on the right, left, or even behind the aircraft. TFR system or TF mode of the main radar of the aircraft will be a tool not only for analyzing meteorological situation but also a tool for visual identification.

The object of the research – The process of implementing terrain-following radar in medium-haul aircraft.

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CHAPTER 1

HISTORY AND PRINCEPLES OF TFR

1.1 Basic information

Before starting I need to input basic information about radar characteristics so there won't be any confusion about the information I will input in this explanatory note.

First of all, a radar is an electrical system that transmits radiofrequency (RF) electromagnetic (EM) waves toward a region of interest and receives and detects these EM waves when reflected from objects in that region. The major subsystems of a radar must include a transmitter, antenna, receiver, and signal processor. The subsystem that generates the EM waves is the transmitter.

The antenna is the subsystem that takes as input these EM waves from the transmitter and introduces them into the propagation medium. There are two basic antenna configurations of radar systems: monostatic and bistatic. In the monostatic configuration, one antenna serves both the transmitter and receiver. To isolate transmitter and receiver from each other such system has transmit/receive(T/R) device (usually a circulator or a switch). The T/R device has the function of providing a connection point so that the transmitter and the receiver can both be attached to the antenna simultaneously and at the same time provide isolation between the transmitter and receiver to protect the sensitive receiver components from the high-powered transmit signal. In the bistatic configuration, there are separate antennas for the transmit and receive radar functions.

The *wavelength, λ*, of the wave is the distance from any point on the sinusoid to the next corresponding point, for example, peak to peak or null (descending) to null (descending). The period is the time it takes the EM wave to go through one cycle. If the period is expressed in seconds, then the inverse of the period is the number of cycles the wave goes through in 1 second. This quantity is the wave's *frequency, f,* it's expressed in hertz. 1 Hz equals one cycle per second. There are different types of EM waves as a function of frequency, from EM telegraphy to gamma rays. Although they are all EM waves, some of their characteristics are very different depending on their frequency. Radars operate in the range of 3 MHz to 300 GHz, though the large majority operate between about 300 MHz and 35 GHz. This range is divided into a number of RF "bands". There different standards of the RF “bands” classification so I will mention only those that will be used in this document.

Table 1.1 shows general representation of RF bands

Table 1.1.

Radio waves frequency bands

Radio waves	Frequency	Frequency Limits, MHz		Wavelengths, meter	
		F_{min}	F_{max}	λ_{max}	λ_{min}
Miriameter waves	Very low frequency (VLF)	0,003	0,03	100000	10000
Kilometer waves	Low frequency (LF)	0,03	0,3	10000	1000
Hectometer waves	Medium frequency (MF)	0,3	3	1000	100
Decameter waves	High frequency (HF)	3	30	100	10
Meter waves	Very high frequency (VHF)	30	300	10	1
Decimeter waves	Ultra high frequency (UHF)	300	3000	1	0,1
Centimeter waves	Super high frequency (SHF)	3000	30000	0,1	0,01
Millimeter waves	Extremely high frequency (EHF)	30000	300000	0,01	0,001

Figure 1.1 shows comparison of different standards

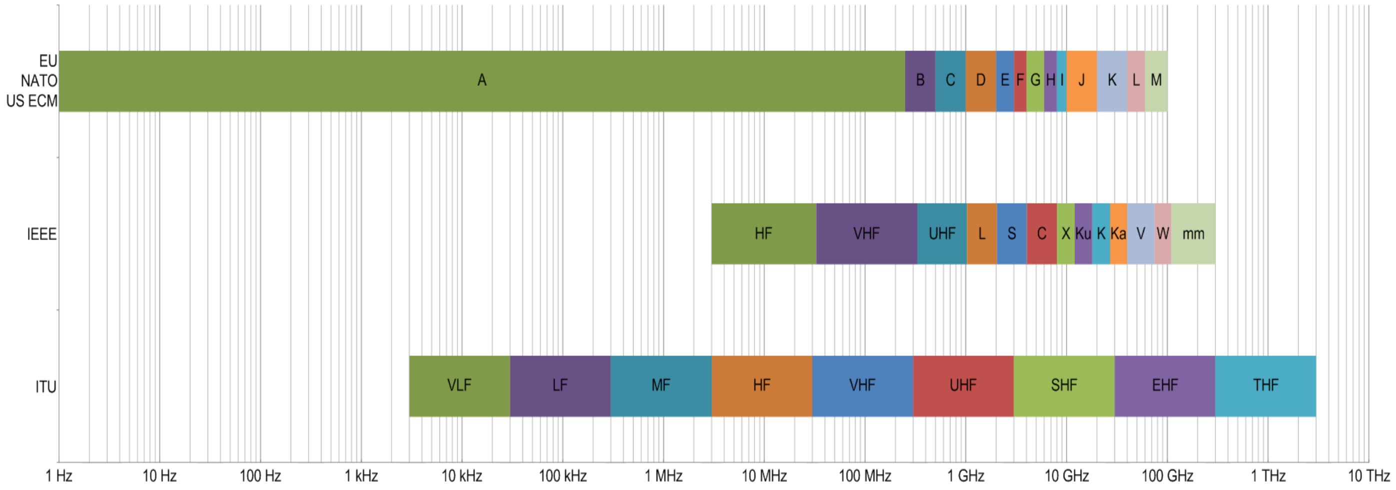


Fig. 1.1. Frequency bands comparison

Table 1.2 shows comparison of NATO standard and IEEE frequency standard.

Table 1.2.

Historical Radar Bands			**NATO/EW Bands**		
Band Designation	**Frequency** GHz	**Wavelength** cm	**Band Designation**	**Frequency** GHz	**Wavelength** cm
VHF	0.03-0.3	1,000-100	**A**	0.03-0.25	1,000-120
UHF	0.3-1	100-30	**B**	0.25-0.5	120-60
L	1-2	30-15	**C**	0.5-1	60-30
S	2-4	15-7.5	**D**	1-2	30-15
C	4-8	7.5-3.75	**E**	2-3	15-10
X	8-12	3.75-2.5	**F**	3-4	10-7.5
Ku	12-18	2.5-1.6	**G**	4-6	7.5-5
K	18-27	1.6-1.1	**H**	6-8	5-3.75
Ka	27-40	1.1-0.75	**I**	8-10	3.75-3
MM3	40-100	0.75-0.3	**J**	10-20	3-1.5
			K	20-40	1.5-0.75
			L	40-60	0.75-0.5
			M	60-100	0.5-0.3

1.2 History of development

The advent of radar in 1940 brought about a drastic change in air combat both on tactical and strategic levels. It gave an enormous advantage to the AA ground defence systems in ways of providing information about hostile aircrafts, by detecting them at long ranges, and neutralizing them before they reached their targets.

Further developments of AAD systems in fifteen years after the end of World War II made use of ground-to-air missiles coupled to sensitive radars with computer control, which made the task of the attacking aircraft extremely dangerous.

One way of countering anti-air defines systems is simple very low altitude flight to approach the target. This works because performance of air defences search radars are limited at low elevation angles because ground echoes, which called “clutter”, from radar’s own transmissions are confusing the system and because terrain, hills especially, is covering a big portion of airspace for search radars. Coupled with little to none time which aircraft is in view of radar makes tracking of aircraft, by radar or optical means, extremely challenging. Thus, anti-air defines systems are left without its long-range radar capabilities, the aircraft has an advantage of surprise effect.

But this method has one penalty which is danger of the aircraft hitting the ground, especially at night or in unacceptable weather conditions. With the goal to assist the pilot in his task of staying close to the ground and yet avoiding obstacles, a particular type of airborne equipment has been developed called, generally, Terrain-Following Radar or simply TFR.

One of the first Terrain-Following radars was developed, built and flown by the Electronic Systems Dept, of *Ferranti Ltd.* in Edinburgh in the mid-1960s. Designed to be mounted in the nose of a low flying aircraft, radar scans the terrain ahead of the aircraft and determines the path in elevation which the aircraft must follow to clear the ground by the required height: this clearance height, selectable by the pilot, can be chosen to be anywhere between 200 and 1000 feet above the ground.

ORAFs: Brian Haffenden

Fig. 1.2. English Electric Canberra low pass

There are two sources about development of the TFR both are from former employees of *Ferranti Ltd*.

“Guidance information for manual flying is produced by the radar on a head-up display or the radar output can be coupled directly to the aircraft auto pilot which will fly the aircraft automatically. The head-up display projects the image of a dot (target spot) and a circle (aiming mark) either on the windscreen or on an auxiliary glass plate which is semi-silvered to enable these symbols to be viewed against a background of the ground ahead of the aircraft.

The symbols are optically arranged to appear at infinity so that no change in focus of the pilot's eyes is required while watching them and the ground. The target spot represents the path which the air craft should be following to clear the ground ahead by the required amount and the aiming mark represents the actual path. For successful terrain following the pilot is required to fly the aircraft so that the aiming mark always encloses the target spot. The radar output drives the target spot up and down with respect to the aiming mark depending on whether the aircraft is required to climb or dive.

Other sources of information are necessary for terrain following. A radio altimeter measures the vertical height above the surface and is used when flying over smooth water which gives no radar returns. A doppler radar is used principally to measure aircraft azimuth drift angle. This angle is used to position the radar scanner in azimuth so that it points along the future aircraft track (i.e. in the direction the aircraft is actually going and not where the nose is pointing). An attitude reference provides signals for roll stabilizing the equipment against aircraft roll movements and an airstream direction detector, also made by *Ferranti Ltd.* at Edinburgh, measures the angle of attack of the aircraft.

The radar aerial scans in the vertical plane over an angle of 20 deg., i.e. plus 8 deg. to minus 12 deg. with respect to a reference line on the aircraft. This reference is taken to be a line through the radar roll axis and all angular measurements are made with respect to this line. As the aerial scans the radar sends out a stream of pulses, and for each pulse the range to the ground along the aerial bore sight is measured; range to the ground at all scanner angles is therefore known. The ground profile which is thus determined is compared with an imaginary curve generated within the radar’s terrain-following computer. The name given to this curve is the ‘ski’ because of its shape and its mode of action is shown in Fig. 1.3 in diagrammatic form.

When the elevation demand is zero, the base of the ski must be parallel to the direction in which the aircraft is flying or, in other words, parallel to its velocity vector. To measure the angle between the reference line on the aircraft (the radar roll axis) and the velocity vector, the airstream direction detector is used. This is a small probe projecting from the side of the aircraft which senses the direction of airflow past the aircraft. The angle measured by the device between the airflow and the radar roll axis datum is fed to the terrain-following computer where it is used to position the base of the ski correctly.

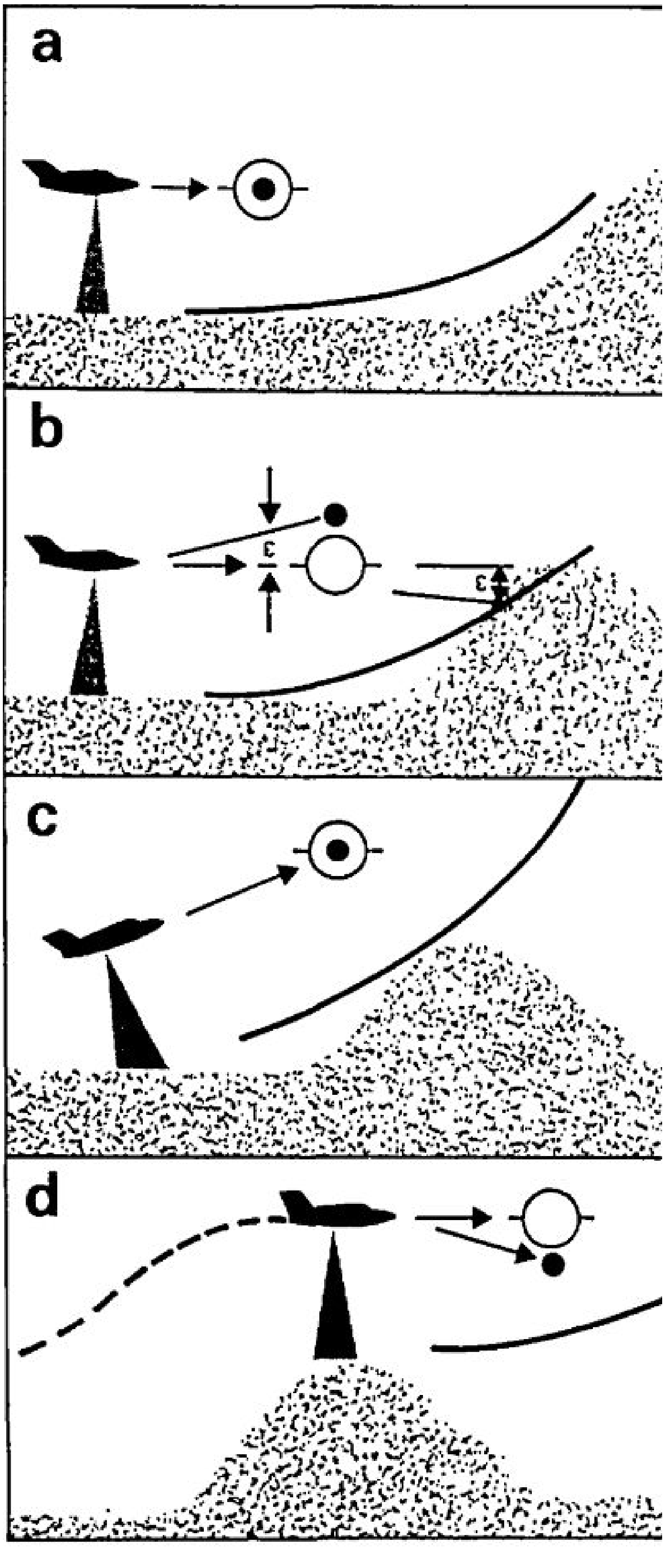


Fig. 1.3. The ‘ski’ in action (see below).

Fig. 1.3a, b, c, d.

(a) The aircraft is shown approaching a small hill. The vertical distance from the aircraft to the base of the ski is equal to the clearance height selected by the pilot and because the ski is just touching the ground the elevation demand is zero. This Is shown by the target spot sitting Inside the aiming circle.

(b) As the hill intrudes within the ski an up demand is generated. This climb demand, of value a is equal to the angle through which the ski must rotate about the aircraft so that it just becomes tangential to the hill.

(c) The pilot pulls up, zeroing the demand and again the target spot sits within the aiming circle. Note that the ski now just touches the hill.

(d) As the aircraft passes over the hill the ground no longer touches the ski and a down demand is generated. The ski will in fact rotate downwards till it touches the ground but the rate at which this happens is controlled so that by keeping the target spot within the aiming circle the pilot never experiences more than a 1/2 g of downward acceleration. This is done to make the ride more comfortable and to keep the contents of the crew's stomachs where they ought to be. Similarly, the design of the ski is such that over most terrain the maximum upward demand does not exceed 1 g.

As the terrain-following radar scans the ground ahead of the aircraft the actual clearance height is measured by the radio altimeter. This height is com pared with the selected clearance height and an up or down demand generated depending on whether the aircraft is flying too high or too tow. This demand is also led to the terrain-following computer and the maximum nose up demand, derived from the radar information or the radio altimeter, is fed, after smoothing, to the head-up display or autopilot.

The computation relies on the radar to provide the range and angle to the ground with the required accuracy. To obtain angular accuracy a monopulse radar system is used (Fig. 1.4). In a simpler non-monopulse radar the aerial produces a single beam whose width is a function of the size of the aerial and the frequency used. A typical beam width in an air borne radar is 4 deg. and any ground within this beam will give a return whose range can be measured but, since the strength of the return can have any value depending on the reflecting properties of the particular piece of ground, its position within the beam cannot be determined. The angular accuracy would therefore be 4 deg. or more, which is quite inadequate for terrain following.

The single-plane monopulse aerial has two feeds simultaneously producing two slightly divergent and overlapping beams, the returns from ground, illuminated by these beams being simultaneously processed in two different ways. A ’sum' signal is formed by adding together the returned signals of each beam. This gives the effect of a single beam equal in width to that of the sum of both beams. At the same time a 'difference' signal is formed by subtracting the returned signal of one beam from the other. This difference signal has a phase which may be compared with that of the sum signal and it also has a minimum amplitude where the beams have equal amplitude, i.e. along the axis of symmetry of the overlapping beams, known as the boresight. When this is done, signals from angles above the boresight arc in phase with the sum signal and produce a positive output and those below the boresight produce a negative output. At the range at which the boresight intersects the ground the subtraction process produces zero output, shorter ranges a negative output and longer ranges a positive output. The exact range along the boresight to the ground can therefore be determined by this method to a fraction of a degree.

The monopulse system is used only in elevation, where accuracy is required. In azimuth, this is not necessary and the full beam-width of the aerial is used.

A particular difficulty which had to be overcome in the development of the terrain following radar was the range of signal strengths which could be encountered. Returns from built-up areas and isolated buildings can be 10 million times (70dB) stronger than those from sand or arid ground and the strength of the return is unfortunately not a measure of its importance since the top of a hill may be a poor reflector. If the receiver is made sensitive enough to see such weak signals, strong reflectors at angles off to one side may swamp it or alternatively may break through the aerial sidelobes and appear at the output as ground at a higher angle than it actually is. Consequently considerable work had to be done in measuring the returns from a wide variety of terrain and in developing an automatic gain control system which would deal with this situation. The equipment had also to provide safe steering signals in elevation while the aircraft navigation system was demanding a turn cither via the autopilot or through the azimuth channel of the head up display. A bank angle of 45 deg. at a Mach number of 0.9 had to be tolerated and to satisfy this requirement it was necessary to arrange that the aerial scan changed from being purely vertical to one which leaned over into the turn. The angle of lean was a function of aircraft bank angle and speed, and ensured that ground was seen sufficiently early to generate any necessary up demand.

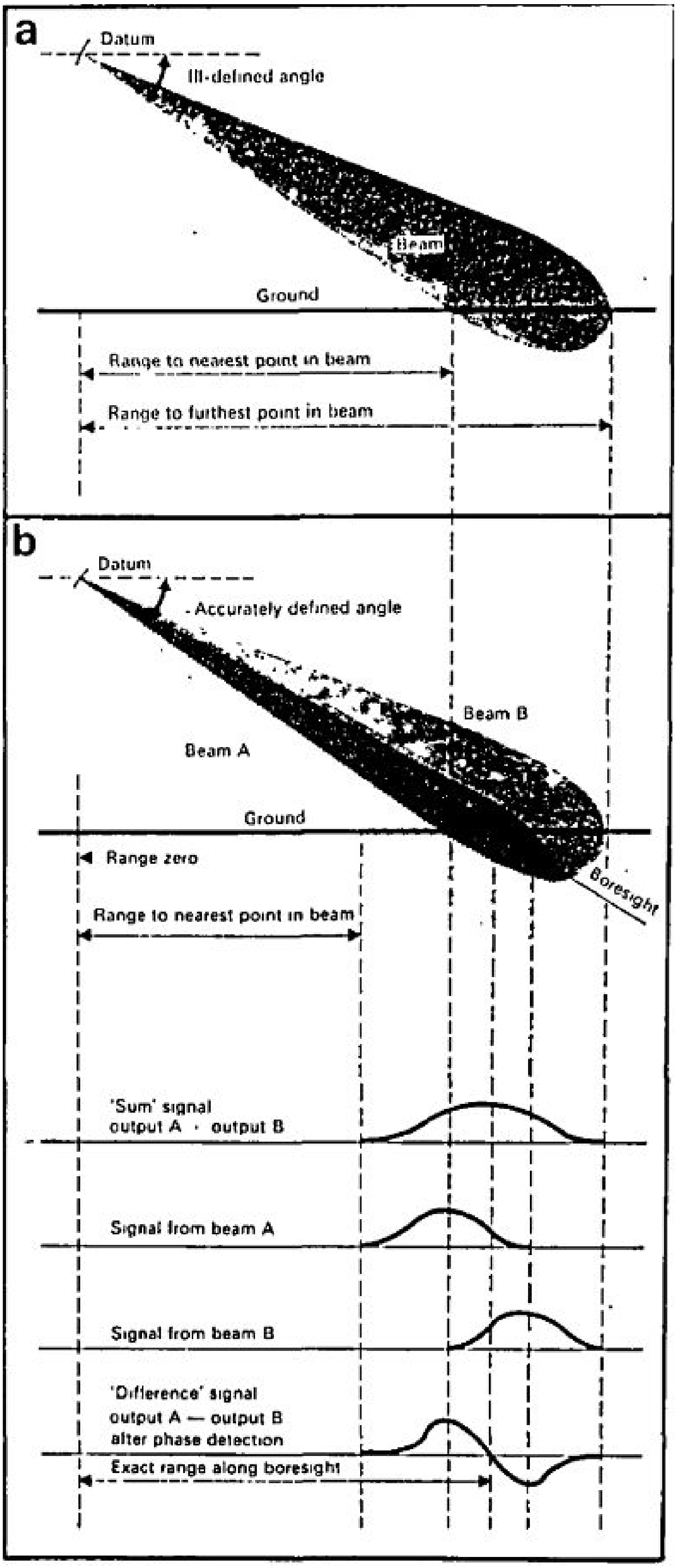


Fig. 1.4. The difference between (a) non-monopulse and (b) monopulse radar systems.

It is obviously essential that any equipment used to fly an aircraft at high speed and low level must not fail in a dangerous manner. To avoid this situation two approaches were used: the equipment was designed and manufactured to have a high inherent reliability and it was also arranged to fail safe; and a built-in monitoring system continuously checked the radar in flight and gave an automatic up demand if a failure was detected.

Semiconductors were used throughout the equipment and these, together with other components, were underrun wherever possible to give increased safety margins. Wrapped joints which had been used and proved in earlier radars were further developed and used for about 90 per cent of wiring and component connections. These and many other design features were backed up by an exhaustive reliability testing programme which subjected the equipment is to simultaneous thermal and vibration cycling while monitoring the equipment performance. Many thousands of equipment proving hours were accumulated with the object of establishing the likely mean time between failures since this could be of considerable value in planning the necessary spares and support to keep the equipment operating in the field.

To test the terrain-following system, two aircraft have been used, a Canberra and a Buccaneer, maintained by the *Ferranti* Flying Unit at Turnhouse Airport and flown both by our own and Ministry sponsored pilots. The aircraft were modified to take the radar and the other equipment forming the system and in addition a considerable amount of instrumentation including several cameras were fitted.

Data such as aircraft flight attitude, radio height, pressure height and important radar parameters were all recorded for analysis after each flight. This information was needed to solve the very difficult problem of determining exactly where the aircraft was with respect to the ground.

Several routes were chosen in order to exercise the system fully over a variety of terrains. These routes included mountains, lakes, rolling countryside, towns and forest areas (Fig. 1.5). The trials also enabled tests to be conducted under varying weather conditions, some times with snow on the ground, and under varying levels of turbulence. The latter phenomenon was of particular interest since it was known to be especially troublesome at low levels and the effect on the pilot's tracking accuracy over a period of time had to be assessed. Prior to these trials varying opinions were held on the length of time the pilot could be expected to terrain-follow manually and an important side of the test flying was to give some idea of the strain such flying imposed on the crew.

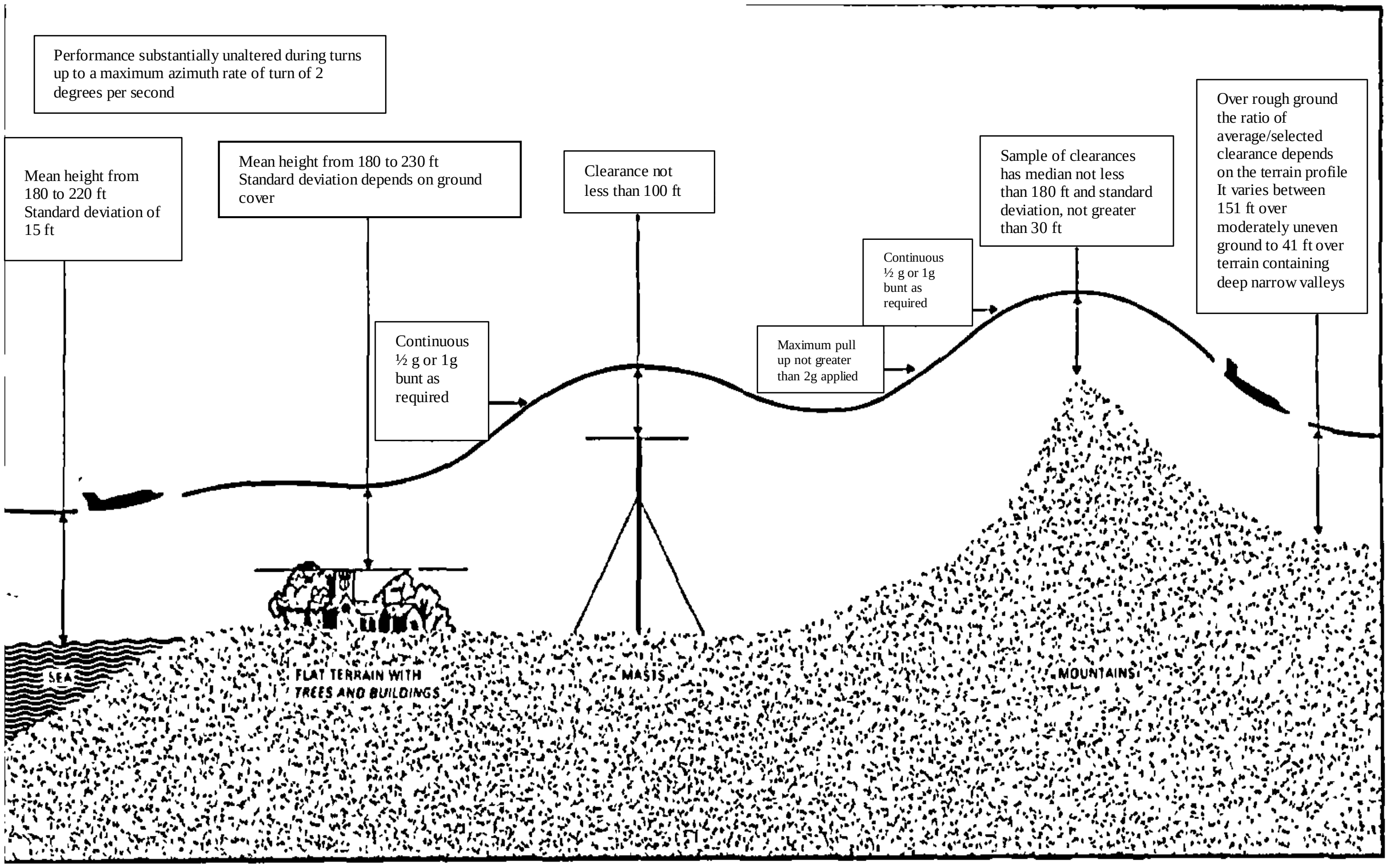


Fig. 1.5. Predicted performance of the system at a clearance setting of 200 ft.

Each test flight provided at least 100 miles of terrain-following data for analysis. Although a prescribed route was flown, small deviations from the planned track had to be allowed for and this was done by finding the actual track flown from the down- ward photographs. The actual profile of the ground was found from the radio and pressure height recordings (maps are not always accurate in this respect) and spot checks on the clearance heights over the main peaks were made by photographing markers placed a known distance apart on these peaks.

All this information enabled a profile of the route flown to be built up and the analyzed aircraft flight path superimposed upon it. This path could then be compared with theory and any deviations would cause data over this part of the route to be specially examined to discover the reason.

Over 250 sorties were flown using different models of the radar and the results can be summarized as follows:

Over flat ground and the sea, height could be held easily to within plus or minus 10 per cent of the height desired. Over rough ground the minimum clearances over hill or mountain tops showed great regularity with a standard deviation better than 30 feet around a mean value within 10 per cent of the selected height.

If the 'wavelength' of the terrain undulations was greater than 3 miles the aircraft would follow the profile closely. As the wavelength became shorter, the flight path tended to be a smoothed version of the profile until, with wavelengths less than 1 mile, the aircraft flew a nearly straight clearance path from crest to crest.

Special flights were also made to investigate particular aspects of the system performance. For example, several flights were made against television towers, the Forth bridges and steep cliffs as these present special problems to a terrain-following system; the flights were, however, entirely successful. Two long flights of over 250 miles were made and it was found that the pilot's tracking accuracy was not significantly worse at the end of the flight than at the beginning nor did the pilot report excessive fatigue, showing that flights of this duration and perhaps longer are entirely feasible. It was not possible to obtain permission to fly at night, which would have shown whether the stress on the pilot was greatly increased but flights were made on several occasions in bad visibility. These conditions, of course, would have little or no effect on equipment operation but do need considerable confidence in the equipment on the part of the crew.

It was noticeable that pilots new to the system gained confidence very quickly, using the lowest clearance height offered within one or two flights.

Moreover their accuracy in tracking almost immediately approached that of pilots who had spent considerable time on the trials programme.

The particular radar described above was designed for a specific aircraft and had other modes of operation. In any new application, such as for the Multi- Role Combat Aircraft, the exact mechanical features and form of a terrain-following radar will depend on the particular installation and on the other elements of the complete terrain-following system, but there is no reason to suppose that the method of operation nor the accuracy of performance will differ greatly from that described.

Flying a modern aircraft at low altitude and high-speed leaves little margin for error and it is thus essential that the pilot has complete confidence in the control system employed. The results obtained with the Ferranti-developed forward-looking radar inspire this confidence" [2].

"During my two years on this project and on the subsequent AI23B radar, I displayed some talent for invention and in making things work. I managed to cut the number of relays from 27 to 14, with essentially the same performance, and made many radical changes and simplifications to the electronics. I also tried to persuade, without success, other analogue computing workers to switch from using served potentiometer systems, for multiplication, division and function generation, to an all-electronic method related to the architecture of the ranging unit.

The proposed TF Radar system was based on a study and some experimental work carried out by Cornell University for the US Department of Defense. The profile of the ground ahead of the aircraft was determined by ground echoes from a vertically scanning radar mounted in the nose of the aircraft. The required flight vector, to maintain a safe low clearance height, was determined by sliding an electronic ski-toe, extending from 1,500 ft to 20,000 ft in front of the aircraft, over the radar derived ground profile. The electronic ski-toe was effectively pivoted at the nose of the aircraft with the flat part of the ski set at the required clearance height below the aircraft. The aircraft flight vector was controlled by the pilot following symbols on a head-up display, or by the aircraft auto-pilot, to be parallel to the flat part of the ski. The clearance height could be set to between 200 and 1200 feet above the flat part of the ski-toe. This caused a smoothed flight path at this minimum height above the highest ground. For close ground hugging, at the expense of a rougher ride, the ski-toe could be bent upwards more abruptly. To avoid 'ballooning' over high hills, an "early climb high" term was added to the flight path calculation. This caused the flight path to be close to horizontal over the peak of the hill.

To avoid problems of not seeing hills close behind other hills, the flight path was limited to a 0.5g down bunt. In addition, for flying over calm water, with very poor radar returns, the required flight path was controlled using height from a radio altimeter. Cornell had not demonstrated the system fully. (My impression, possibly wrong, was that the USA Department of Defence had abandoned interest in the system as it was deemed unlikely to be satisfactory.)

Our major systems work was resolving the problem of excessive elevation errors and noise. Early conical scan radars derived the position of a target by moving the centre of the conical scan until the signal, from the shoulder of the beam, did not vary during the scan. These radars had to perform a complete circular scan, with many transmitted pulses to determine the direction of a target. The modern AI23B monopulse radar derived sum and difference elevation and azimuth signals, for returns from each transmitted radar pulse. It suitably combined the signals received by the four waveguide feeds facing the parabolic antenna. In the AI23B Lightning radar, these difference signals fed the elevation and azimuth antenna servos to track the aerial boresight onto the target selected by the ranging unit range gate. In the TSR2 TF radar, the elevation difference signal was used to determine if any ground was above the Antenna boresight (positive signal) - or below (negative signal). As the aerial performed a vertical scan ahead of the aircraft, any positive signal return above the electronic ski-toe, drove the ski-toe upwards until no positive returns were received. Thus the electronic ski-toe rested on top of the highest point of the radar derived profile of the ground ahead. With the aircraft flight vector controlled to be parallel to the ski-toe flat bottom the aircraft flew a smoothed path close to the ground.

The analogue computing method, that I had previously derived from the A23 Ranging Unit, proved ideal for generating the required ski-toe range gate as function of scanner elevation angle and also for the subsequent feedback loop filtering to derive the smoothed required flight vector. I designed the changes to this thermionic valve based unit on the trials AI23B radar to implement this system. Brian Pitches and John Morrison designed the transistor version for the final TSR2 radar and also did a lecture tour round Ferranti on this novel analogue computing system.

Once the system had been trialled extensively and successfully at the Linlithgow site it was installed in Canberra WT327 at Turnhouse during the very cold winter of 1961-62.

A radar corner reflector was cited on the course to check radar alignment to the Head Up Display (HUD). Polarities and correct scaling of the signals to the Head Up display, showing the actual and required flight vectors, were checked by azimuth movement of the aircraft and by jacking it in pitch and roll. The complete fitting and subsequent checking of the system took about four months.

1.3 Subsequent studies

Subsequent studies are mostly focused on improving accuracy and performance of the TFR system. One of such, “A New Approach for Terrain Following Radar Based on Radar Angular Superresolution”, studies a new signal processing method to improve angular accuracy of the TFR system.

“In traditional TFR system, the aerial produces a single beam whose width is a function of the size of the aerial size and the frequency used. The beam width is big, which is quite inadequate for terrain following. In order to obtain better angular accuracy of TFR, we proposed a novel method based on scanning aerial and radar angular superresolution.

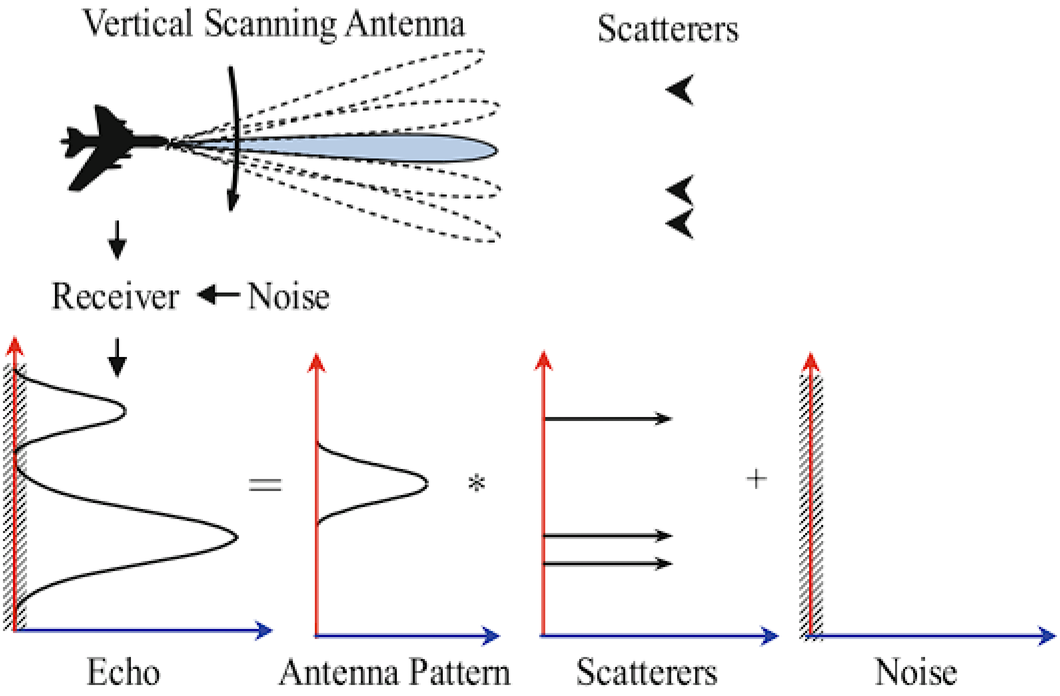


Fig. 1.6. Signal model of TFR

The signal model of TFR is shown in Fig. 1.6. The baseband video output signal will trace out the antenna voltage pattern as it scans past a scatterer in the vertically direction, if two scatterers are close together, the output voltage will be proportional to the superposition of two replicas of the antenna pattern. The echoes in vertical direction are the convolution of the antenna pattern and the surface scatterers when radar scanning a region vertically, antenna pattern is equivalent to the angular impulse response. Consider return signal at one range bin: x(φ) denotes the surface scatterers, h(φ) and n(φ) denote antenna pattern and noise respectively. Then signal model of the return is expressed as

$$s(\varphi)=x(\varphi)*h(\varphi)=n(\varphi) \qquad 23.8$$

where s(φ) is return signal, ∗ indicates convolution operator. We can recast this equation (23.8) in the frequency domain as

$$S(\omega)= X(\omega)H(\omega)+N(\omega) \qquad 23.9$$

where ω is spatial frequency. In time domain, the output voltage will be proportional to the superposition of many replicas of the antenna pattern, modulation of antenna pattern leads to the poor azimuth resolution. In frequency domain, typical antenna pattern results in strong low-pass filtering, and low resolution in the output data results from filtering out high spatial frequencies from the true scene. Based on signal model, we can restore the scatterers by deconvolution. In theory, using knowledge of the operator inverse H^{-1} can restores surface scatterers:

$$\tilde{s}(\varphi) = H^{-1}\, s(\varphi) = x(\varphi) + H^{-1}n(\varphi) \qquad 23.10$$

In frequency domain, (23.10) can be expressed as

$$\tilde{S}\,(\omega)=S(\omega)/H(\omega)=X(\omega) + N(\omega)/H(\omega) \qquad 23.11$$

In practice, conventional inverse filter does not work. Since H(ω) has zeros for spatial frequencies above some cutoff value, it results in tremendous amplification of noise. Thus, the deconvolution becomes an ill-posed inverse problem. To overcome this problem and obtain radar angular super-resolution, various regularization methods are proposed in *Radar angular superresolution algorithm based on Fourier-wavelet regularized deconvolution* (2013). *Improving angular resolution based on maximum a posteriori criterion for scanning* *radar* (2012). *Radar angular superresolution algorithm based on Bayesian approach* (2010).

The range migration is apace-variant for TFR, and it can be corrected using the keystone transform. Moreover, the angular resolution of TFR can be greatly improved using the angular superresolution algorithm. Simulation result validates that the method can effectively improve the angular accuracy of TFR in vertical plane. In the future, this method will be evaluated on the extended target and measured data." [4].

1.4 Analyzation of the system

Principle of operation of TFR lies in transmitting a pencil beam radar signal towards the ground area in front of the aircraft while the radar scans up and down. The signal is sent as a series of brief pulses and the reflections of these pulses off the ground produces very powerful returns. The time the pulse takes to travel to and from the terrain produces a range measurement to the terrain in front of the aircraft. The angle relative to the aircraft is returned by a sensor on the vertical gimbal that returns a calibrated voltage.

Indication of the preferred flight path works in a way of representing on a HUD a dot and a circle that should align to guide aircraft on preferred flight path, or at the same time that the radar is sending out pulses, a function generator is producing a varying voltage representing on a E-scope(side view) indicator a preferred maneuvering curve which. This is similar in shape to a ski jump ramp, flat under the aircraft and then curving upward in front of it. The curve represents the path the aircraft would take if it was maneuvering at a constant g-force, while the flat area under the aircraft extends forward a short distance to represent the distance the aircraft moves in a straight line before starting that maneuver due to control lag. The resulting compound curve is displaced by a pilot-selected desired clearance distance.

The timing of the pulses is much faster than the vertical scanning, so for any one pulse the angle is fixed. When then pulse is sent, the function generator is triggered. When the return is seen, the system sums the output from the generator at that instant with the output from the angle sensor on the radar. The resulting voltage represents the angle between the actual and preferred location. If the voltage is positive, that means the terrain lies above the curve, negative means it is below. This difference is known as the *angle error*.

To guide the aircraft, a series of these measurements are taken over the period of one complete vertical scan out to some maximum distance on the order of 10 nautical miles. The maximum positive or minimum negative value of the angle error during the scan is recorded. That voltage is a representation of the change in pitch angle the aircraft needs to fly at to keep itself at the desired clearance altitude above the terrain while maneuvering at the selected load factor This can be fed into an autopilot or displayed on the pilot's heads-up display. This process produces a continually computed path that rises and falls over the terrain with a constant maneuvering load.

One problem with this simple algorithm is that the calculated path will keep the aircraft in positive pitch as it approaches the crest of a hill. This results in the aircraft flying over the peak while still climbing and taking some time before it begins to descend again into the valley beyond. This effect was known as "ballooning". To address this, real-world units had an additional term that was applied that caused the aircraft to climb more rapidly against larger displacements. This resulted in the aircraft reaching the desired clearance altitude earlier than normal and thus levelling off before reaching the peak.

Because the radar only sees objects in the line-of-sight, it cannot see hills behind other hills. To prevent the aircraft from diving into a valley only to require a hard pull-up, the negative G limit was generally low, on the order of 1 G. The systems also had problems over water, where the radar beam tended to scatter forward and returned little signal to the aircraft except in high sea states. In such conditions, the system would fail back to a constant clearance using a radio altimeter.

Terrain avoidance normally works in a relative fashion; that is, the absolute altitudes of objects are not important. In some cases, it is desirable to provide an absolute number to indicate the amount of clearance or lack of it. The height of the top of any particular feature relative to the aircraft can then be calculated through $h = H - R \sin \varphi$, where H is the altitude over the ground measured by the radio altimeter, φ is the angle and R the range measured by the radar, with h being the resulting height of the object over the current flight path. The clearance between the aircraft and terrain is then H - h.

Conclusion to chapter 1

TFR system makes it possible to fly at ultra-low altitudes relatively safely and at a constant altitude. TFR allows to automate the process of flying at low altitudes, thus relieving a certain percentage of the pilots' workload and facilitating their role in controlling the aircraft. System gives enough room for crew to react on a changing terrain and even take control, if paired with autopilot, over the aircraft to avoid possible collision with ground and buildings.

CHAPTER 2

ANALYSATION OF AIRCRAFTS WITH TFR

2.1 General Dynamics F-111e

The General Dynamics F-111 Aardvark was an American supersonic, medium-range interdictor and attack aircraft. Developed in the 1960s by General Dynamics, it first entered service in 1967 with the United States Air Force. F-111 was a pioneer aircraft to be first in history service aircraft equipped with an automated terrain-following radar for low-level, high-speed flight. The aircraft was equipped with AN/APQ-110 terrain-following radar. The AN/APQ-110 was a Ku-band terrain-following radar manufactured by Texas Instruments [5].

AN/APQ-110 terrain following radar has 3 modes of operation: terrain following, situation (SIT) and ground mapping (GM), SIT and GM models are pitch, drift and roll stabilized, while TF mode is only roll and drift stabilized. [7] In TF mode, the radar scans in vertical pattern with narrow 8 degrees beam, it scans 8 degrees above the centre line of the aircraft and 32 degrees below it. It is the only computerized mode. [7] The maximum detection range of this mode is 10 nautical miles (18.52 kilometres). [6] In SIT mode the radar scans in horizontal pattern with same 8-degree beam for a 60-degree view to detect obstacles in front, on the same altitude as the aircraft or above it. [7] The maximum detection range of this mode is 15 nautical miles (24.14 kilometres). [6] GM mode is similar to the SIT mode but its scanning area is tilted down up to 15 degrees. [6,7]

“The terrain following radar (TFR) provides low altitude terrain following, terrain avoidance and blind let-down capability. The TFR consists of left and right antenna receivers, synchronizer transmitters, power supplies and computers in a dual channel configuration; a radar scope panel and a control panel. Each channel may be operated independently of the other in any one of three modes: terrain following (TF), situation display (SIT), or ground mapping (GM). The TFR receives inputs from the radar altimeter, attack radar, bomb-nav system or auxiliary flight reference system, central air data computer and flight control system. Refer to figure 2.6. The TFR operates on 115 volt ac power from the main ac bus and 28 volt dc power from the main dc bus.

TERRAIN FOLLOWING (TF) MODE. The TF mode allows the aircraft to be flown manually or automatically at a preselected terrain clearance. Climb and dive signals generated in the manual and automatic mode can be coupled into the attitude director indicator (ADI) and lead computing optical sight (LCOS). In the manual mode, the set clearance can be maintained by flying pitch steering commands on the ADI or LCOS. In the automatic mode, the climb and dive signals are coupled into the pitch channel of the flight control system. Refer to the figure 2.5. The TF mode can also be used to make blind let-downs to a preselected terrain clearance in either the manual or automatic mode. Should the aircraft descend to below 68 percent of the selected terrain clearance altitude setting, or if a TF malfunction is detected, the TFR will indicate a fly-up command on the ADI/LCOS and the flight control system will initiate a fly-up manoeuvre if the aircraft is being flown manually or is in auto TF.

The initial aircraft response to the fly-up command may be as much as +3.8 absolute g-s.

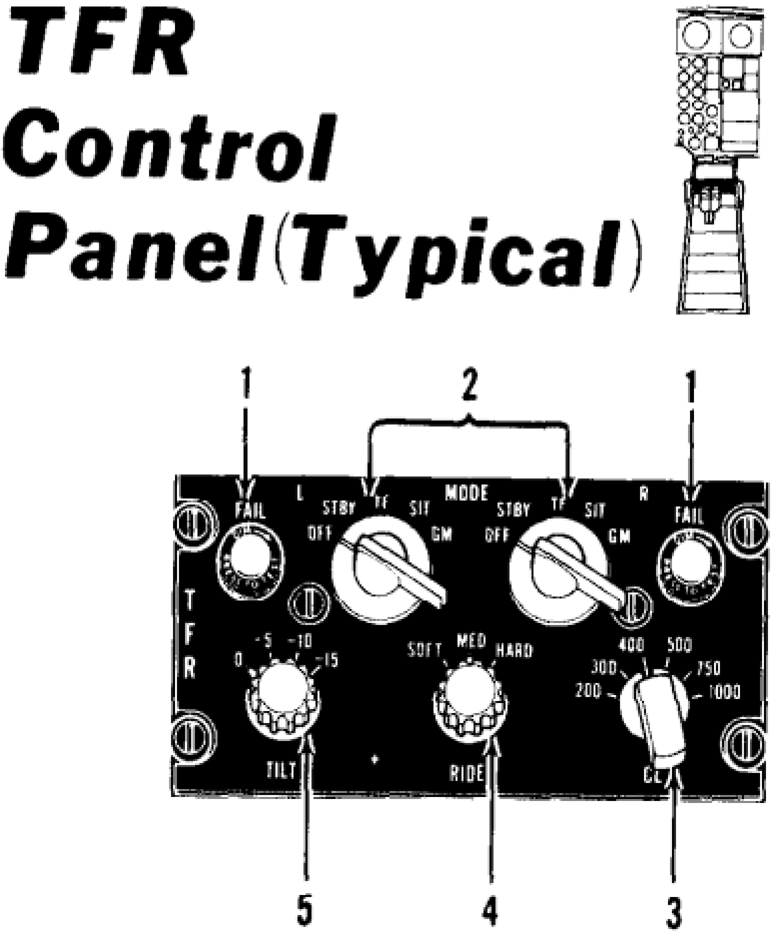
SITUATION MODE (SIT). This mode of operation is used in conjunction with the TF mode for obstacle avoidance. In this mode, the antenna is pitch and drift stabilized such that the antenna scans in the horizontal plane thirty degrees on each side of the aircraft ground track. Returns from terrain that extend above the altitude of the aircraft are displayed on the scope in a one-radius offset plan position indication with range selections of 5, 10, and 15 miles with fixed cursors provided for range reference at 1, 2, and 5 miles respectively. The information displayed on the scope allows the pilot to choose a flight path which avoids major obstacles.

GROUND MAP (GM) MODE. The antenna scan and stabilization, and type of scope display in this mode are the same as in the SIT mode. The targets displayed in this mode are those which are being illuminated by the complete pencil beam from the antenna. The antenna tilt can be adjusted to optimize the target display by rotating the antenna tilt knob on the TFR control panel. The range of tilt control is from 0 degree to 15 degrees below the horizontal reference.

AIR-TO-GROUND RANGING MODE. This mode is used in conjunction with the attack radar to provide range-to-target data to the LCOS when an air-to-ground weapon delivery mode is selected on the LCOS. The mode enabling command signal is routed within the TFR to whichever channel is in the SIT or GM mode.

TFR CONTROLS AND INDICATORS.

TFR Channel Mode Selector Knobs. Two five-position rotary channel mode selector knobs (2, figure 2.1), located on the TFR control panel, permit selection of the desired operating mode in each of the two channels. The knobs are labeled L and R for the respective channel and are individually marked OFF, STBY, TF, SIT, and GM. In the OFF position, power is removed from the channel. In the STBY position, power is applied to the channel for warm-up. The TF, SIT and GM positions provide terrain following, situation display or ground mapping modes of operation respectively. If both knobs are positioned to TF the second channel will automatically go to a standby condition, then should the operating channel fail the one in standby will automatically take over after a momentary fly-up occurs. If the R channel is in control and a failure occurs (even a momentary failure) the L channel will take over and the R channel will go to standby. Another failure will switch the operation back to the R channel. Any subsequent failures will not cause automatic switchover until the L channel is recycled to STBY position and back to TF. In other words it will cycle R-L-R and stay in R. If the L channel starts out in control a fail will cause a switchover to the R and stop there until the L channel is recycled.



1. TFR Channel Failure Caution Lamps (2).
2. TFR Channel Mode Selector Knobs (2).
3. Terrain Clearance Knob.
4. Ride Control Knob.
5. Antenna Tilt Control Knob.

Fig. 2.1. TFR control panel

Terrain Clearance Knob. The terrain clearance knob (3, figure 2.1), located on the TFR control panel, has six positions marked 200, 300, 400, 500, 750 and 1000(feets). Rotating the knob clockwise increases the altitude clearance setting corresponding to the position selected and vice versa. Note When flying at one clearance setting and the knob is positioned to a higher setting, a TF failure and fly-up may be generated until the aircraft is maneuvered outside the 68 percent radar altimeter fly-up range. The TFR should maintain flight within the following tolerances. If these tolerances are not maintained the equipment should be written up after the flight. If an undershoot occurs to the extent that a 68 percent fly-up occurs, change to the other channel. If the fly up again occurs select the next higher setting. Do not operate at the lower setting where the 68 percent fly up occurred.

Selected Clearance	Terrain Clearance	
	Min.	Max.
200 ft	170	300 ft
300 ft	260	425 ft
400 ft	350	550 ft
500 ft	440	650 ft
750 ft	675	950 ft
1000 ft	900	1200 ft

During automatic terrain following flight over level to rolling terrain or other water with HARD ride selected, the radar altimeter should indicate the altitude above the terrain corresponding to each clearance knob setting within these tolerances. Terrain clearances when cresting peaks will usually be slightly less than the stabilized, level terrain clearances. The above tolerances are not directly applicable to terrain following flight over rugged terrain; however, terrain clearances when cresting peaks should not consistently be below these tolerances. Clearances may be slightly higher in SOFT or MED relative to the HARD ride clearances.

Ride Control Knob. The ride control knob (4, figure 2.1), located on the TFR control panel is a three position rotary knob marked SOFT, MED, and HARD. The negative commanded g’s will be limited to zero for HARD, 0.5 for MED, and 0.75 for SOFT. The fail-safe fly-up signal is not affected by the position of this switch. Progression of the ride control from HARD to SOFT will compute an earlier anticipatory command upon approach to an obstacle.

Antenna Tilt Control Knob. The antenna tilt control knob (5, figure 2.1), located on the TFR control panel is used to position antenna tilt between zero and -15 degrees for the best ground return when operating in the GM mode. The knob will continuously vary the antenna position between zero and -15 degrees. The knob has antenna tilt angles of 0, -5, -10 and - 15 marked for reference. The tilt control is inoperative when the channel mode selector knob is in the STBY, TF, or SIT positions.

Range Selector Knob. The range selector knob (5, figure 2.2), located on the TFR scope panel, has four positions marked 5, IO, 15 and E. The first three positions change range of the scope presentation when using SIT or GM modes. The E position is used with the TF mode only.

Radar Scope Tuning Control Knobs. Four radar scope tuning control knobs (4, figure 2.2), located on the TFR scope panel provide a means of adjusting the scope to obtain the best display. The knobs are labelled CURSOR, MEMORY, CONTRAST and VIDEO from top to bottom. The cursor knob adjusts the brilliance of the range cursors. The memory knob increases or decreases scope storage retention time. The contrast knob adjusts scope contrast for optimum viewing. The video control adjusts the video return brightness to desired level. To obtain the proper video threshold on the TFR scope adjust the contrast control in the E mode until a thin vertical line along the right side of the scan becomes discernible and then adjust the video control for optimum target display. With this procedure, the video paint on the E scope is at approximately the same threshold level as that required by the system for proper commands from the forward-looking radar, and, when switching between any of the positions on the range selector knob (5, 10, 15, E), the scope display should not bloom or fade excessively.

Autopilot Release lever. When flying auto or manual TF the autopilot release lever (6, figure 2.3), located on the control stick grip, may be used for overriding fly-up maneuvers induced by loss of the data good signal from the TFR. When the autopilot release lever is depressed, a pseudo data good signal is sent to the flight control system to interrupt the fly-up. The TF failure warning lamp will not go out when the autopilot release lever is depressed. The fail caution lamp on the TFR control panel will remain lighted as long as the fail condition is present in the TFR.

The auto terrain following (auto TF) switch (3, figure 2.4), located on the autopilot/damper panel, is a two-position lever lock switch marked AUTO TF and OFF. The switch is locked in the OFF position and must be pulled out to move from OFF to AUTO TF.

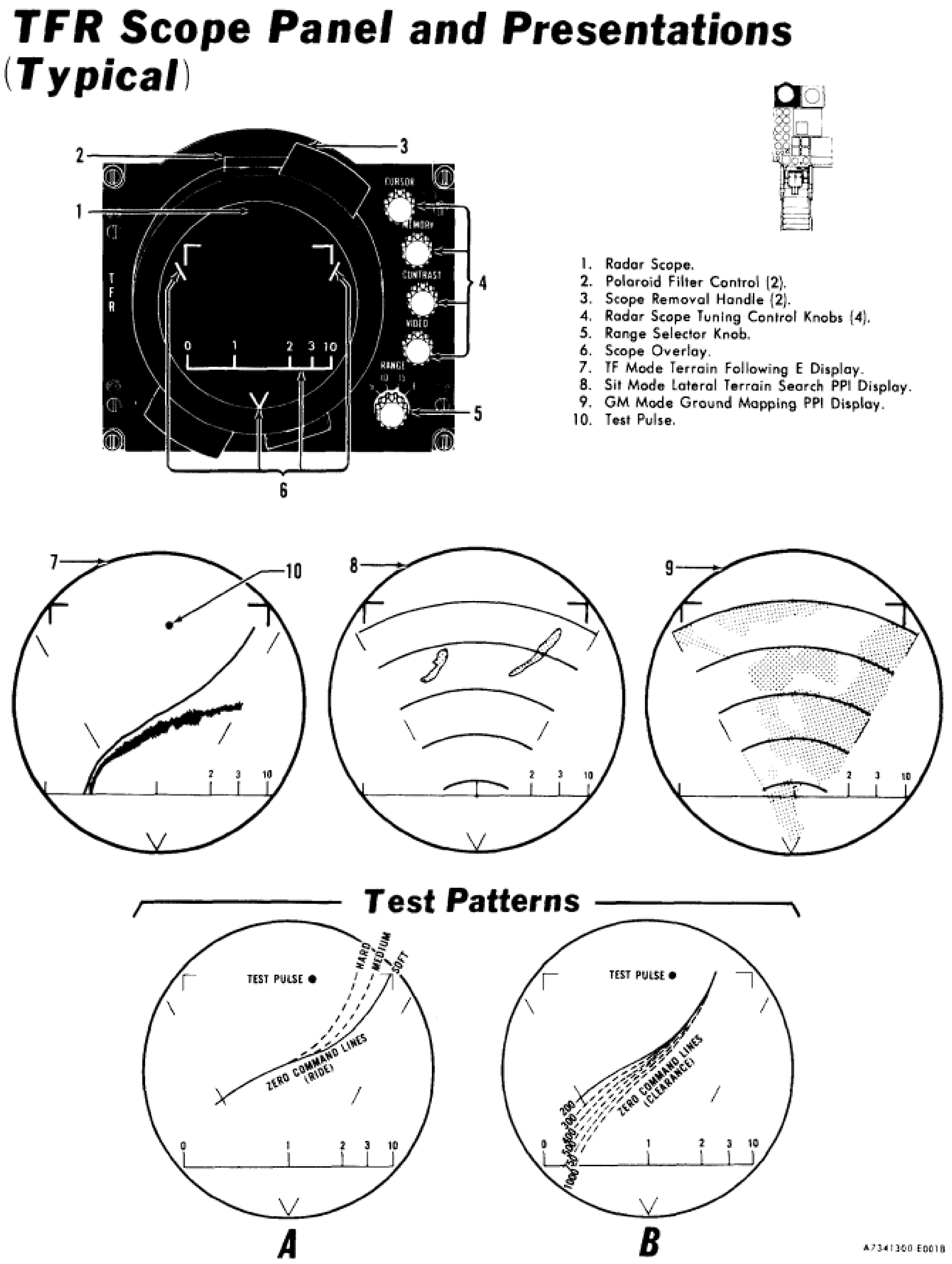


Fig. 2.2. TFR scope panel and presentations

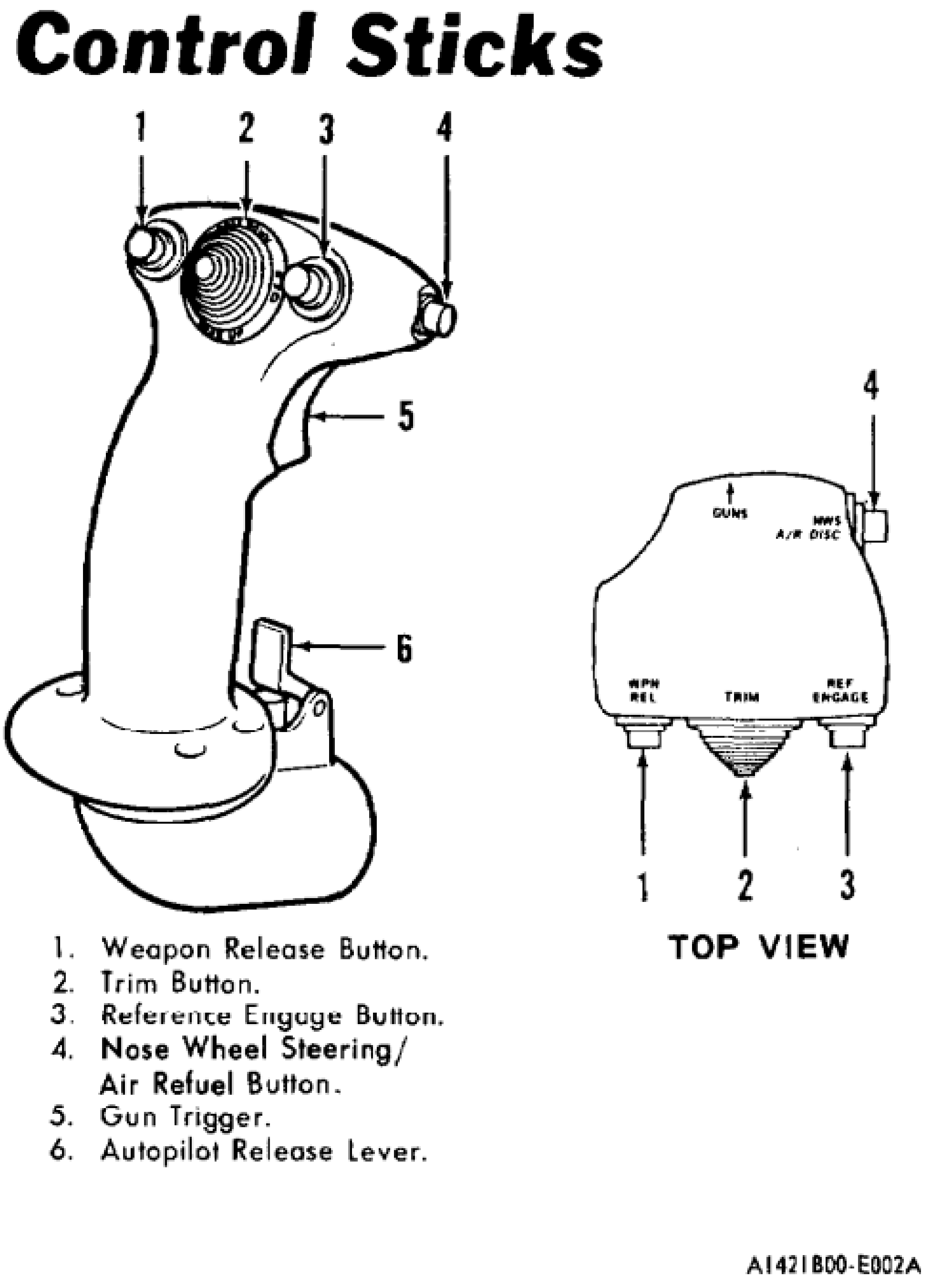


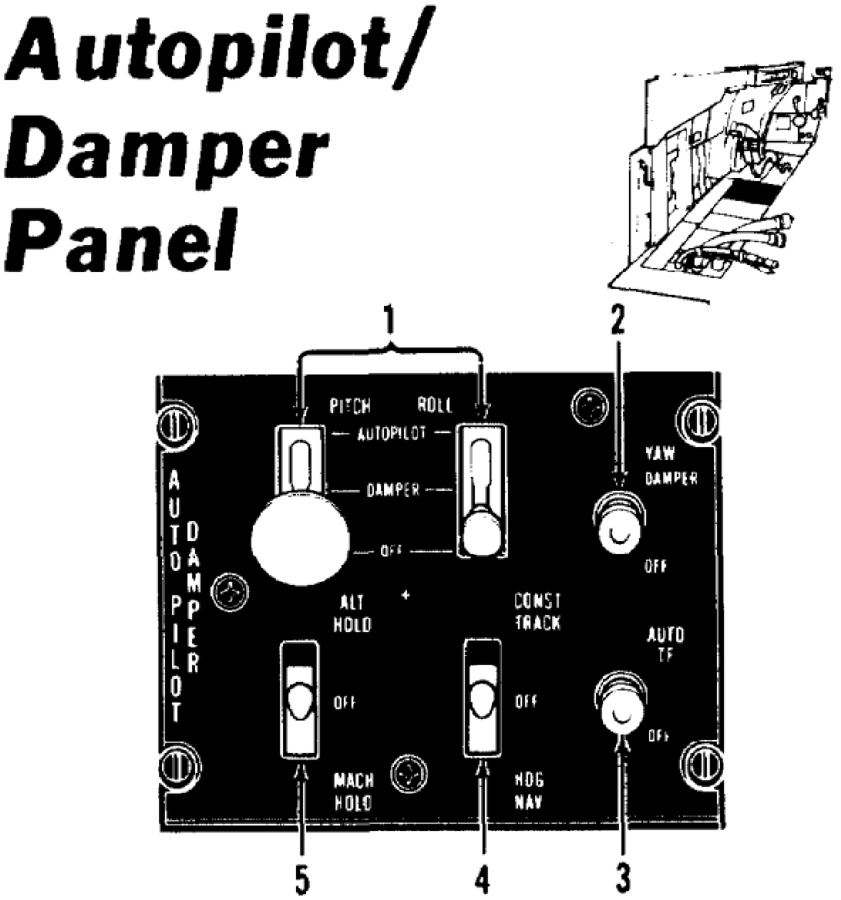
Fig. 2.3. Control sticks

When the switch is in the OFF position and either TFR channel mode selector knob is in the TF position, the aircraft must be flown manually using the pitch steering commands on the ADI and LCOS to hold the terrain clearance selected on the TFR terrain clearance knob. With the switch in the OFF position the reference not engaged lamp will remain on. When the switch is placed to the AUTO TF position and either TFR channel mode selector knob is in the TF position signals from the TFR will control the pitch damper and series trim to automatically fly the aircraft on the terrain clearance setting selected by the terrain clearance knob. The reference not engaged lamp will go out when the auto TF mode is engaged.

Note

When auto TF is selected at least one TFR channel must be in the TF mode to prevent abnormal series trim operation. The fly-up off caution lamp and the reference not engaged lamp will be lighted for this configuration.

When the AUTO TF position is selected, and the auto- u pilot release lever is not held, parallel trim will centre and the control stick may move. If auto TF mode is selected, the pitch trim function of the stick trim button will be inoperative.”[6]



1. Pitch and Roll Autopilot Damper Switches.
2. Yaw Damper Switch.
3. Auto Terrain Following Switch.
4. Constant Track/Heading Nav Mode Selector Switch.
5. Altitude Hold/Mach Hold Selector Switch.

Fig. 2.4. Autopilot/Damper panel

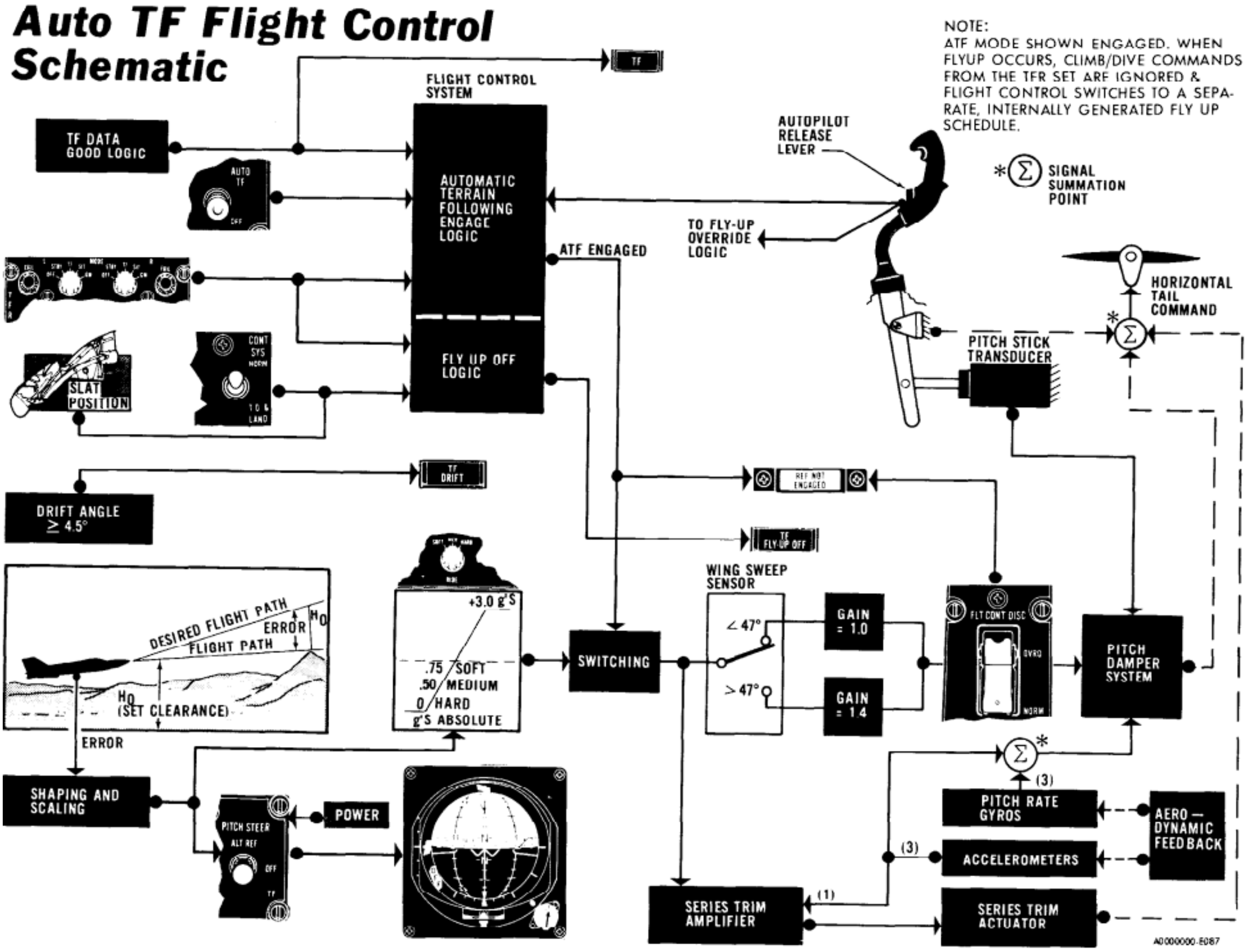


Fig. 2.5. Auto TF flight control schematic

2.2 AN/AAQ-13 LANTIRN Navigation pod

LANTIRN is not an aircraft but a suspension module that gives an aircraft a terrain following capability.

The AN/APN-237 LANTRIN, which stoods for “Low Altitude Navigation and Targeting Infrared for Night”, is a system consisting of two pods AN/AAQ-13 Navigation pod and AN/AAQ-14 Targeting pod. It was developed for use on the fighter aircraft, such as F-15E, F-16(block 40/42 and further variations) and later F-14B(C/D) but only targeting pod was installed on F-14s.

The AN/AAQ-13 nav pod is interesting to us because it carries its own terrain-following radar. AN/AAQ-13 LANTIRN is the first terrain-following radar system to be able to take advantage of digital technology.

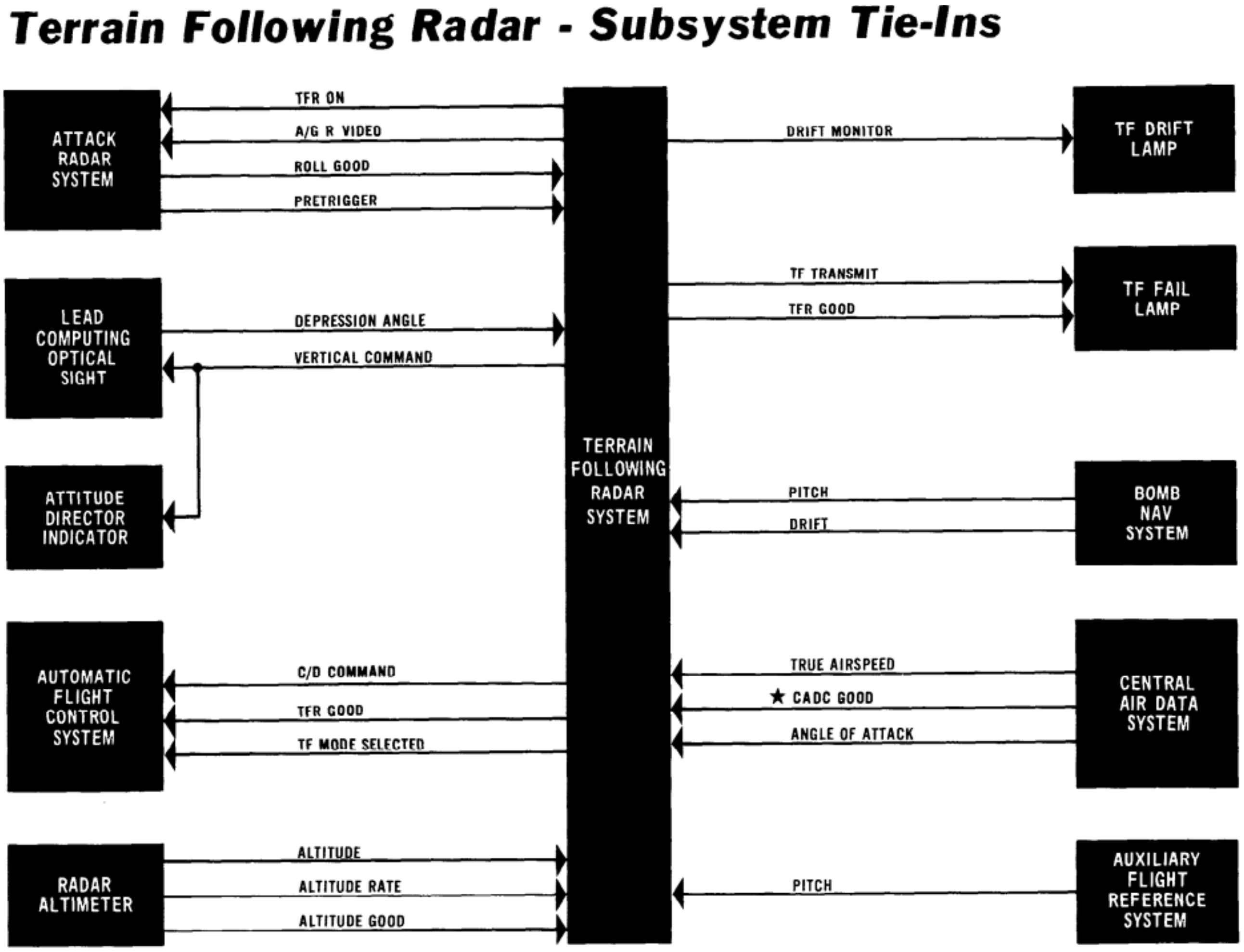


Fig. 2.6. TFR subsystems tie-ins

The nav pod by itself is relatively small, weight: 470 pounds (211.5 kg), length: 78.2 inches (199 cm), diameter: 12 inches (30.5 cm), which means that the system can be kept small if necessary.

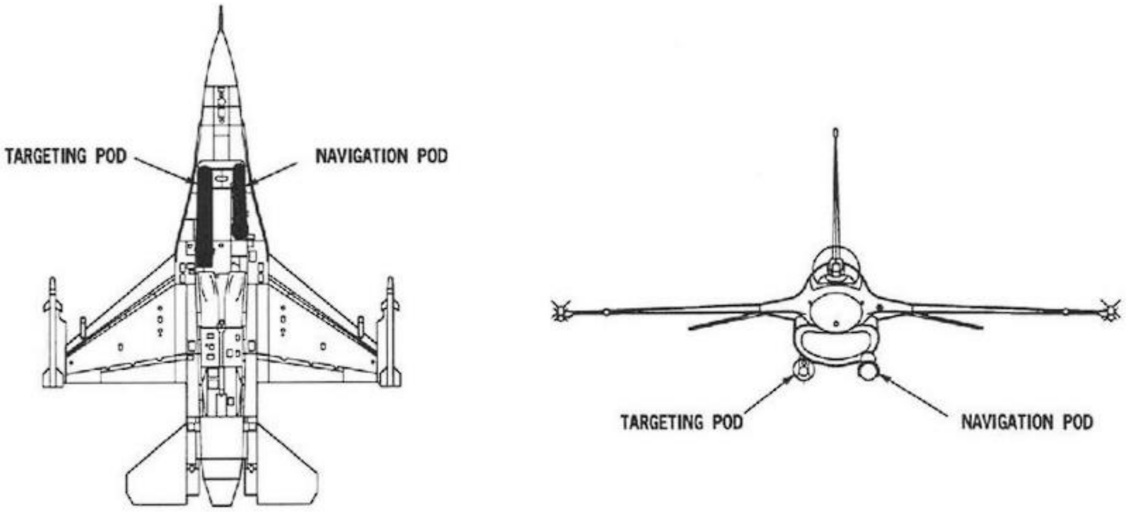
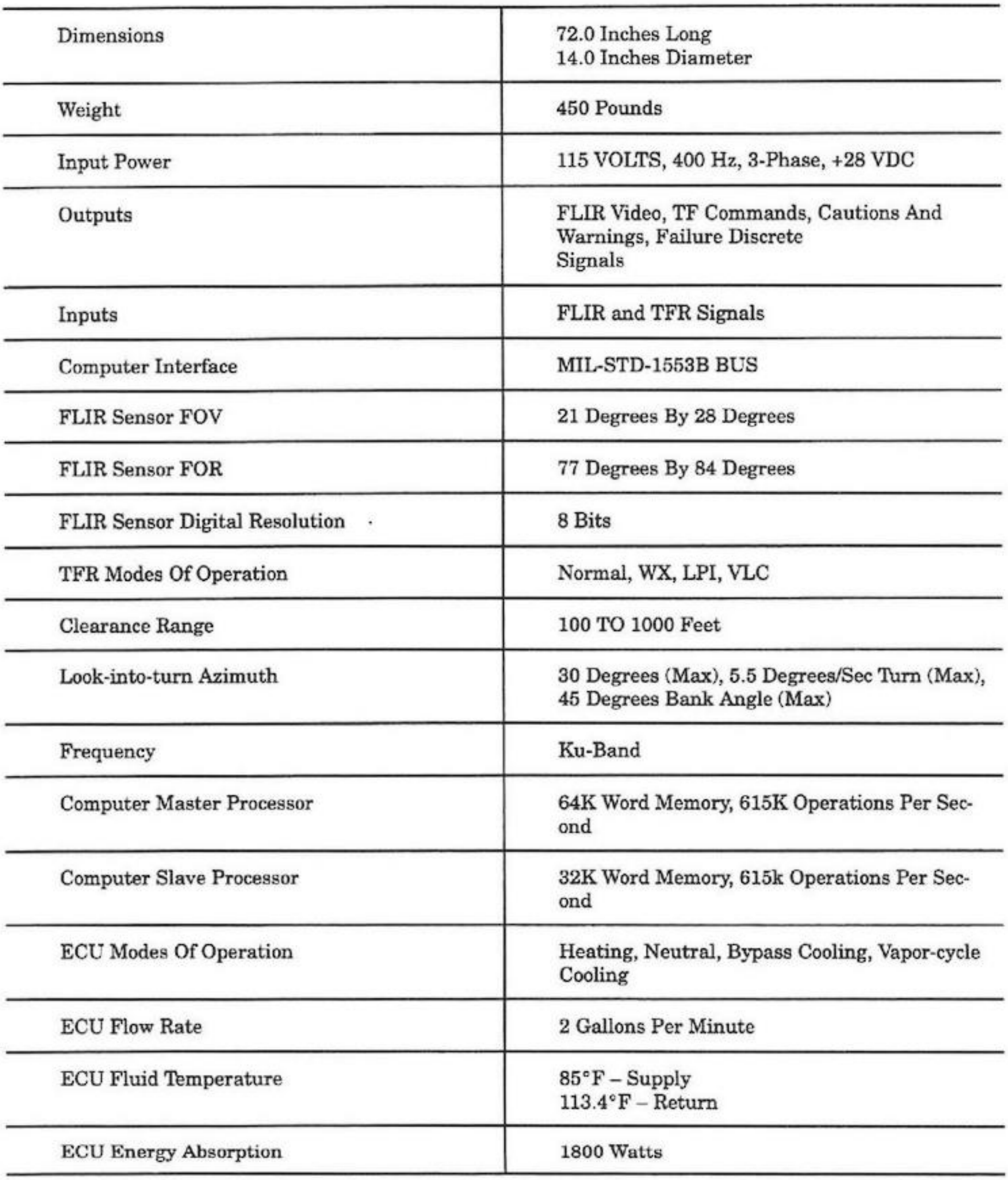


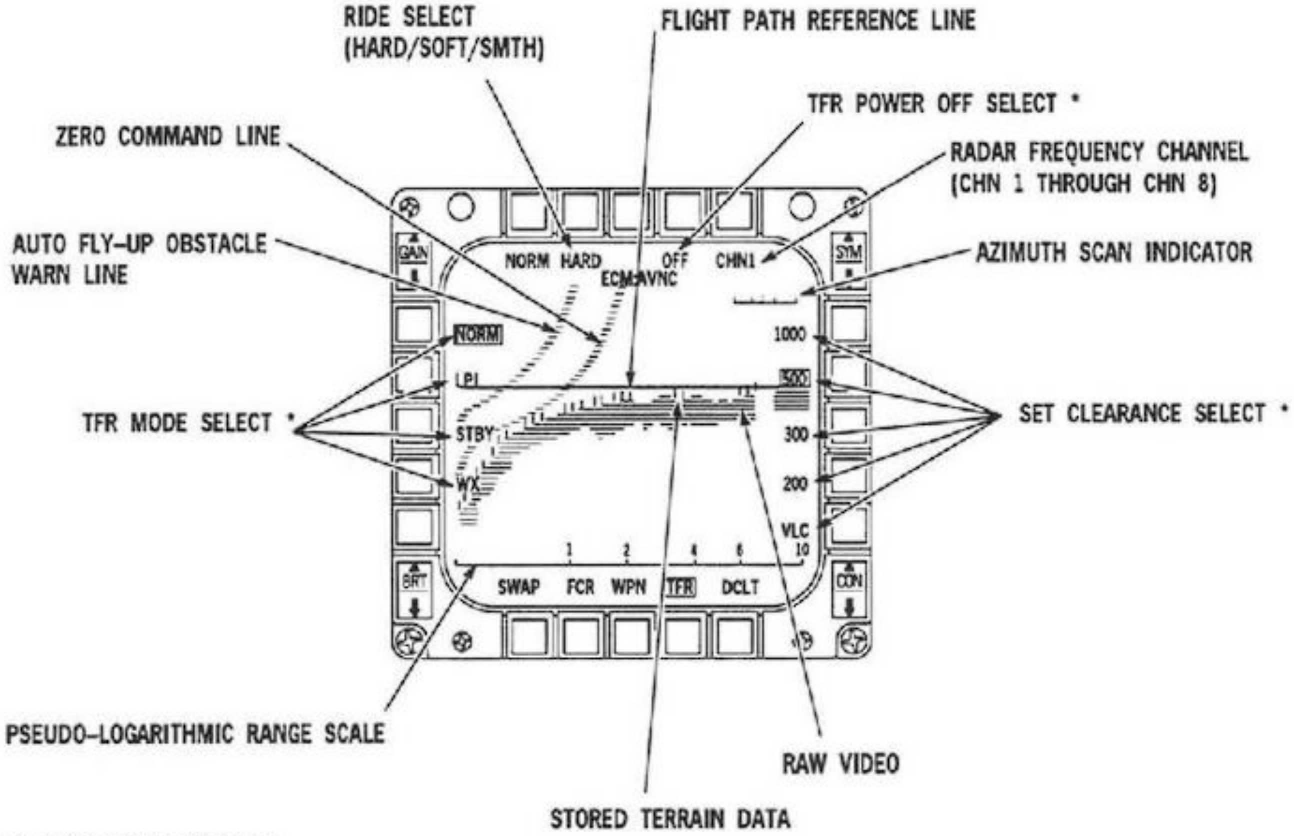
Fig. 2.7. Pod size in comparison to F-16C block 50



Dimensions	72.0 Inches Long 14.0 Inches Diameter
Weight	450 Pounds
Input Power	115 VOLTS, 400 Hz, 3-Phase, +28 VDC
Outputs	FLIR Video, TF Commands, Cautions And Warnings, Failure Discrete Signals
Inputs	FLIR and TFR Signals
Computer Interface	MIL-STD-1553B BUS
FLIR Sensor FOV	21 Degrees By 28 Degrees
FLIR Sensor FOR	77 Degrees By 84 Degrees
FLIR Sensor Digital Resolution	8 Bits
TFR Modes Of Operation	Normal, WX, LPI, VLC
Clearance Range	100 TO 1000 Feet
Look-into-turn Azimuth	30 Degrees (Max), 5.5 Degrees/Sec Turn (Max), 45 Degrees Bank Angle (Max)
Frequency	Ku-Band
Computer Master Processor	64K Word Memory, 615K Operations Per Second
Computer Slave Processor	32K Word Memory, 615k Operations Per Second
ECU Modes Of Operation	Heating, Neutral, Bypass Cooling, Vapor-cycle Cooling
ECU Flow Rate	2 Gallons Per Minute
ECU Fluid Temperature	85°F – Supply 113.4°F – Return
ECU Energy Absorption	1800 Watts

Fig. 2.8. Navigation Pod Design Parameters

“Control and display of TFR information arc accomplished on the TFR page of the MFD (figure 2.9). The TFR has three ride control settings, five set clearance selections, and five mutually exclusive modes. In addition, E-squared video is displayed to provide confidence that the TF system is responding properly to the sensed terrain.



* HIGHLIGHTS WHEN SELECTED

Fig. 2.9. TFR page on the MFD

The TFR ride options are selected via the OSB adjacent to the ride select rotary and are as follows:

- HARD
- SOFT
- SMTH (smooth).

The TFR set clearance options are selected via the OSB’s adjacent to the set clearances along the right side of the MFD. The set clearance options are as follows:

- 1000 feet
- 500 feet
- 300 feet
- 200 feet
- VLC.

The TFR mode options are selected via the OSB’s adjacent to the modes displayed along the left side of the MFD. The mode options are as follows:

- NORM
- LPI (low probability of intercept)
- STBY
- WX (weather)
- VLC (very low clearance) - Not displayed as a TFR mode option, but automatically selected when in NORM and the VLC option is selected. VLC mnemonic appears near the upper left and lower right OSB’s when VLC mode is in use.

The TF E-squared display, displayed whenever the TFR is operating and the TFR page is accessed, provides terrain following anticipation via an E-squared presentation, i.e., elevation angle relative to the aircraft versus pseudo-logarithmic range (figure 2.9). The declutter option may be selected by depressing the OSB adjacent to DCLT. The TFR NOT TIMED OUT mnemonic is displayed in the upper area of the MFD during TFR warmup.

Terrain video is displayed from right to left. Terrain video is displayed to the left side of the E-squared presentation representing terrain closest to the aircraft. The zero command line (ZCL) is a graphic display of the commanded flightpath, and the horizontal flight vector line is displayed as a flightpath reference line. An obstacle warn line is also shown on the E-squared display to indicate that a pull up of 4.0 incremental g's is needed to clear the terrain. Small rectangular symbols displayed with the video represent processed video (stored terrain). The shaded area underneath the rectangular symbols represents unprocessed (or raw) video from the primary bar the TFR is using to generate g-commands. The raw video may be used to identify ECM and weather conditions.

The relative position of each reference changes as a function of terrain, velocity, set clearance, ride selection, and the flight vector. For example, changing the ride selection from HARD to SOFT will move the upper portion of the ZCL as shown in figure 2.10.

Comparing the HARD and SOFT rides, the HARD ride allows the aircraft to fly closer to an obstacle before commanding a climb. The E-squared display reflects this by moving the upper portion of the hard ride ZCL into a closer range.

The ZCL changes as a function of set clearance plane (SCP) as shown in figure 2.11. Changing to a lower SCP raises the lower portion of the ZCL, causing a gap between the ZCL and the terrain. In auto TF, this results in the aircraft pushing over and stabilizing at the new SCP. If a higher SCP is selected, the lower portion of the ZCL will move down, thus penetrating the terrain and causing a climb in auto TF.

The raw video is shown out to approximately 10 nautical miles on the E-squared display. The stored terrain is also shown out to approximately 6 nautical miles except when in WX mode. In these modes, the stored terrain and the ZCL are only displayed out to approximately nautical 2.5 miles.

For NORM and VLC modes, the TFR scans -20 degrees and +10 degrees from the computed center of scan; for WX mode, the TFR scans —20 degrees and +5 degrees; and for LPI mode, upper scan limit is +5 degrees and the lower limit is variable. For level or climbing flight, the center of scan is always along the aircraft’s flightpath as in figure 2.12. For diving flight, the center of scan is at one-half the flight vector angle (figure 2.13). See figure 2.14 for scan pattern detail.

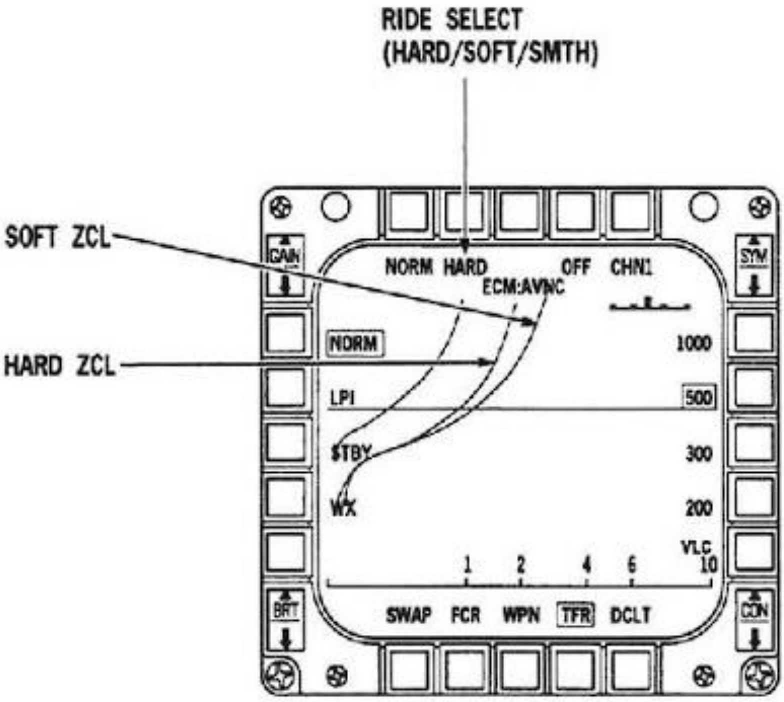


Fig. 2.10. Ride Selection Effect on ZCL

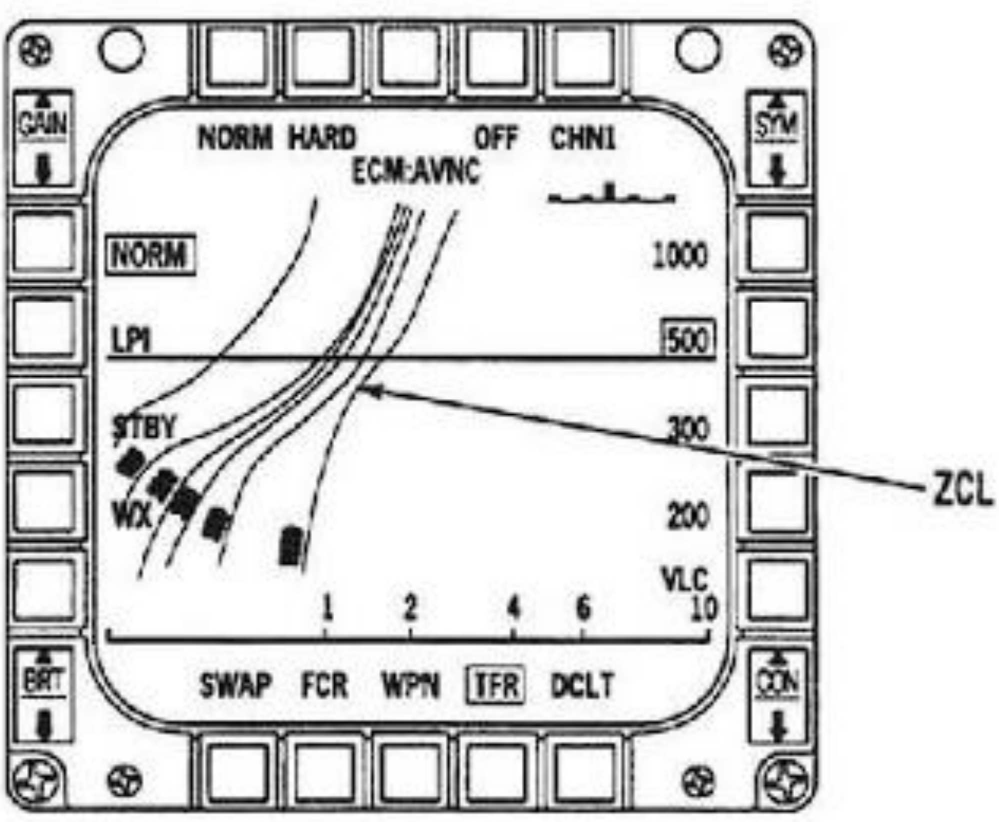


Fig. 2.11. Set Clearance Plane (SCP) Effect on ZCL

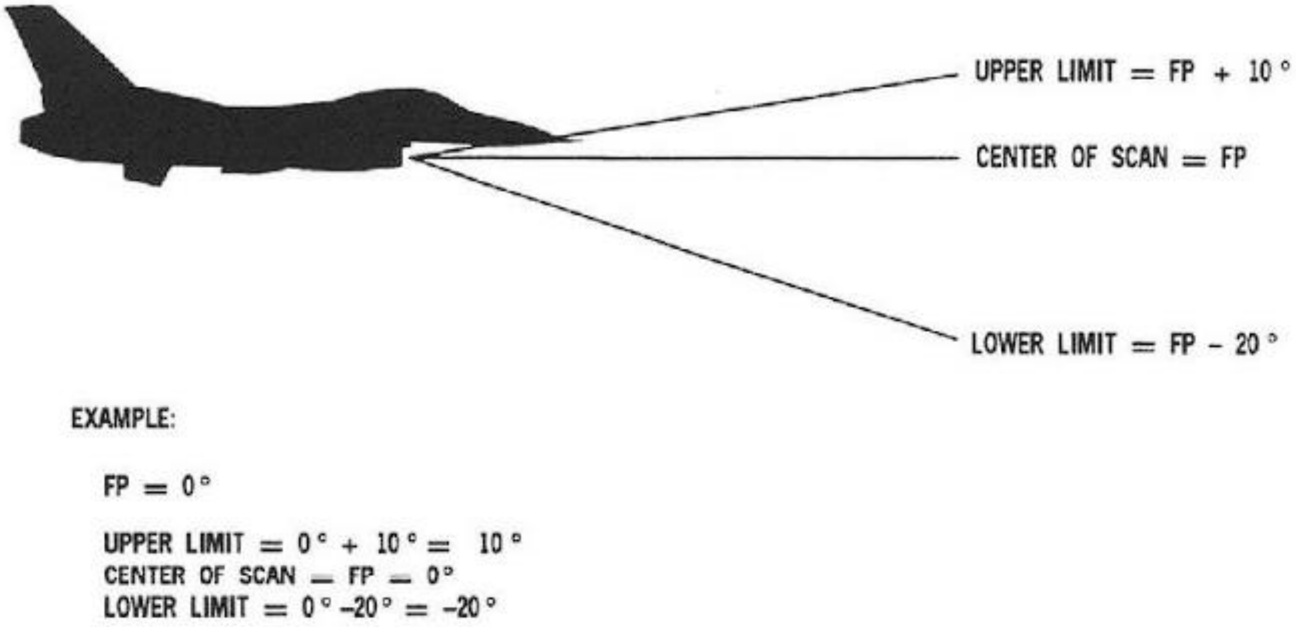


Fig. 2.12. TFR Antenna Scan Limits While Level or Climbing (FP > O) (Typical)

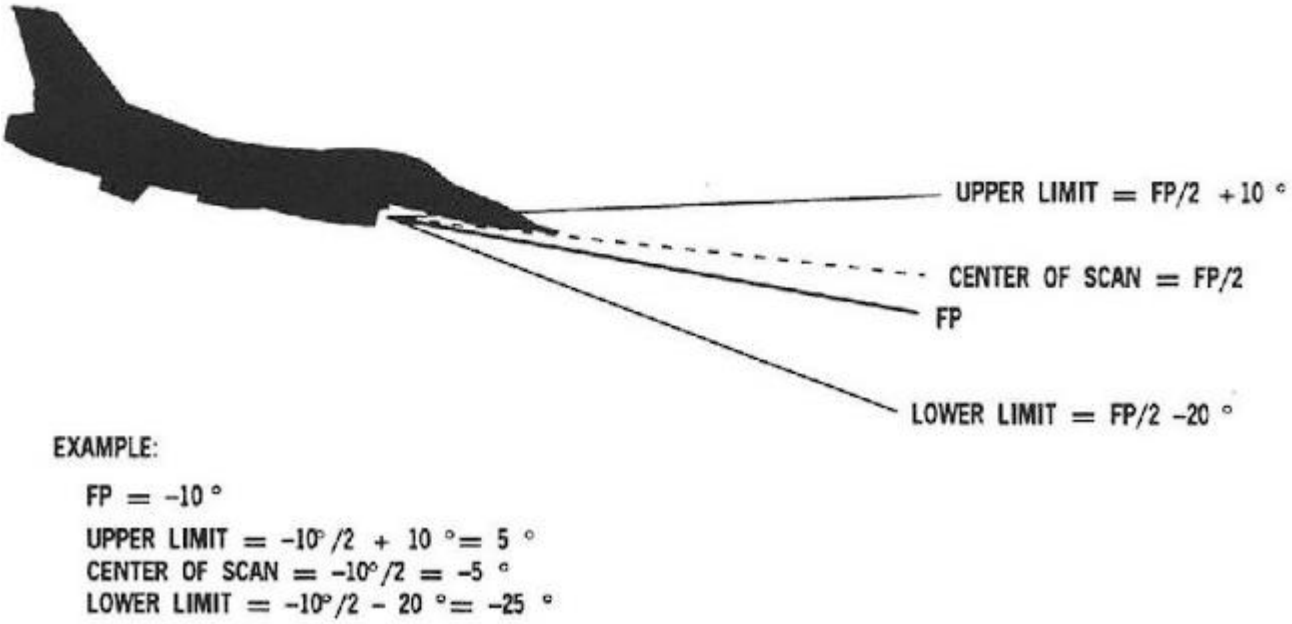


Fig. 2.13. TFR Antenna Scan Limits While Diving (FP < O) (Typical)

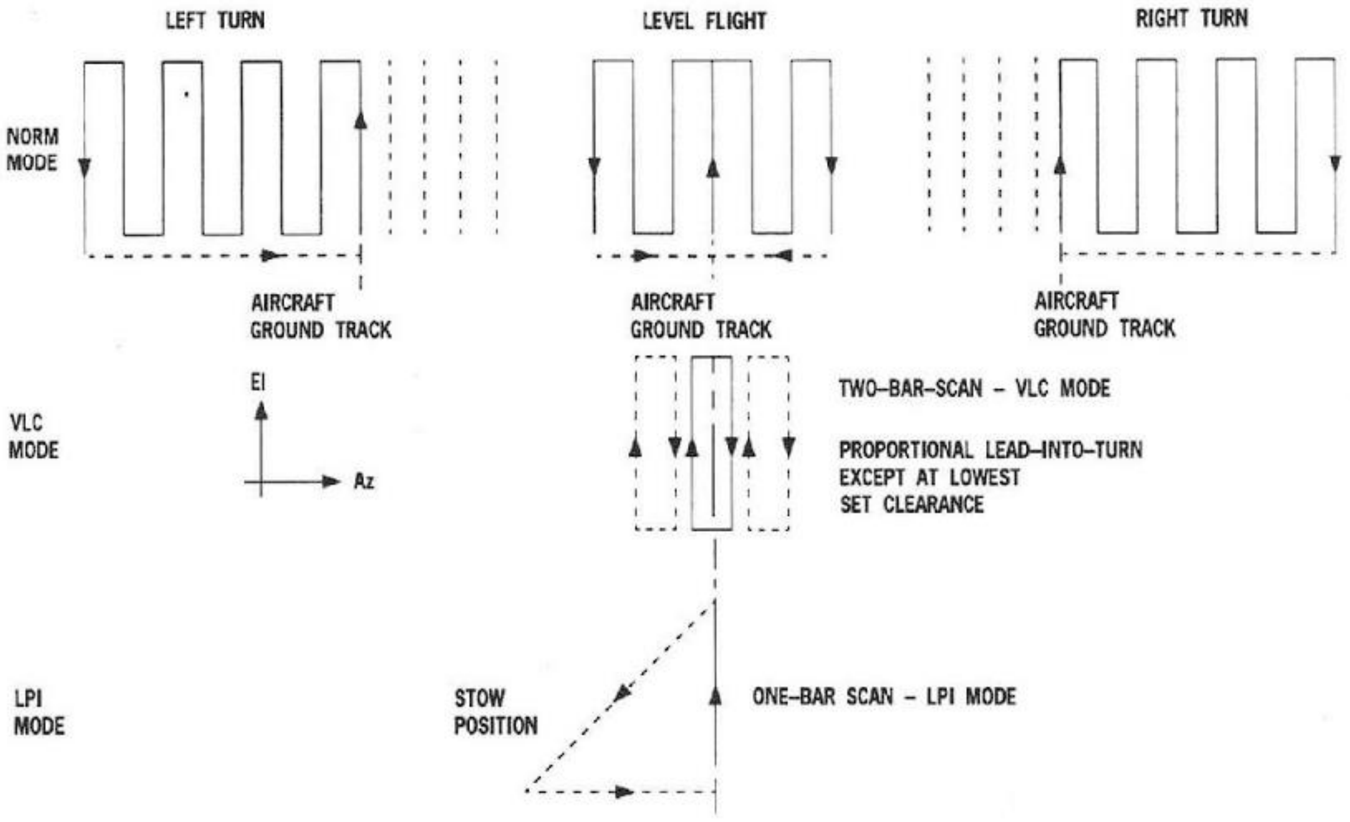


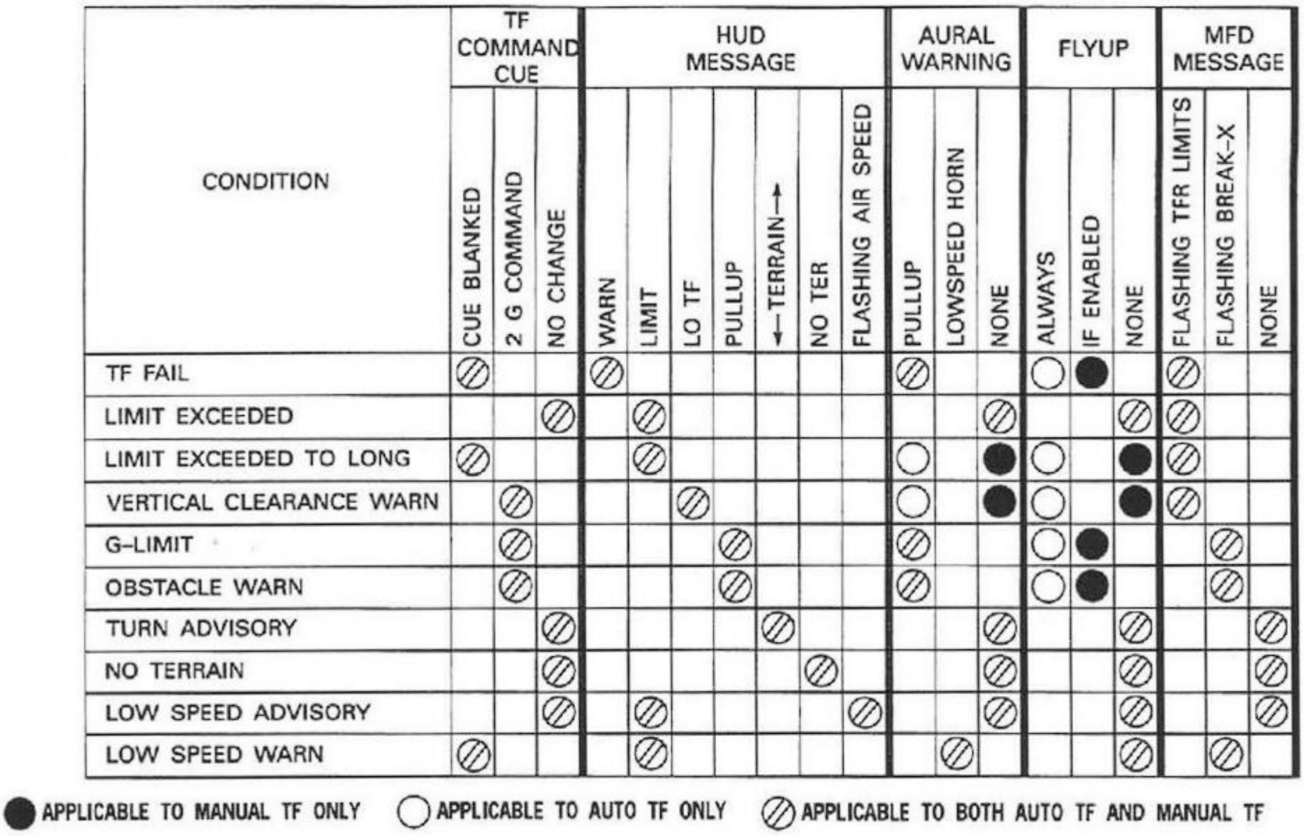
Fig. 2.14. TFR Scan Patterns

The horizontal flightpath reference line indicates the aircraft’s flight vector angle relative to a computed center of scan (the center of scan is always considered to be at the zero-degree position on the E-squared display, as in figure 2.15). For level or climbing flight, the center of scan is along the aircraft’s flight vector. Therefore, the flightpath reference line is at the same position as the center of scan (zero-degree position on the E-squared display). For diving flight, the center of scan maintains a position equivalent to one-half of the flight vector angle, resulting in the flightpath reference line being positioned at one-half of the flight vector angle from the center of scan. For example, a flight vector angle of-10 degrees results in a center of scan of-5 degrees. Since the center of scan is always at the zero-degree position on the E-squared display, the flightpath reference line is at -5 degrees.

Fig. 2.15. Antenna Positions on E-Squared Display

TF WARNINGS, CAUTIONS, AND ADVISORIES

If the TFR fails (as detected by either the NVP or the FLCS), the TF FAIL light on the glareshield illuminates, WARN is displayed on the HUD, and the aural pull up message is activated. Terrain following should not be attempted until the failure has been identified and cleared. When the TFR is operating in maximum threshold, (TFR performance degraded) steady chevrons are displayed on the HUD. Other warnings, cautions, and advisories are displayed as detailed in figure 2.16 and in figure 2.17.” [8]



CONDITION	TF COMMAND CUE			HUD MESSAGE							AURAL WARNING			FLYUP			MFD MESSAGE		
	CUE BLANKED	2 G COMMAND	NO CHANGE	WARN	LIMIT	LO TF	PULLUP	←TERRAIN→	NO TER	FLASHING AIR SPEED	PULLUP	LOWSPEED HORN	NONE	ALWAYS	IF ENABLED	NONE	FLASHING TFR LIMITS	FLASHING BREAK-X	NONE
TF FAIL	⊘			⊘							⊘			○	●		⊘		
LIMIT EXCEEDED			⊘		⊘								⊘			⊘	⊘		
LIMIT EXCEEDED TO LONG	⊘				⊘						○		●	○		●	⊘		
VERTICAL CLEARANCE WARN		⊘				⊘					○		●	○		●	⊘		
G–LIMIT		⊘					⊘				⊘			○	●			⊘	
OBSTACLE WARN		⊘					⊘				⊘			○	●			⊘	
TURN ADVISORY			⊘					⊘					⊘			⊘			⊘
NO TERRAIN			⊘						⊘				⊘			⊘			⊘
LOW SPEED ADVISORY			⊘		⊘					⊘			⊘			⊘			⊘
LOW SPEED WARN	⊘				⊘							⊘				⊘		⊘	

● APPLICABLE TO MANUAL TF ONLY ○ APPLICABLE TO AUTO TF ONLY ⊘ APPLICABLE TO BOTH AUTO TF AND MANUAL TF

Fig. 2.16. Manual and Auto TF Warnings, Cautions, and Advisories

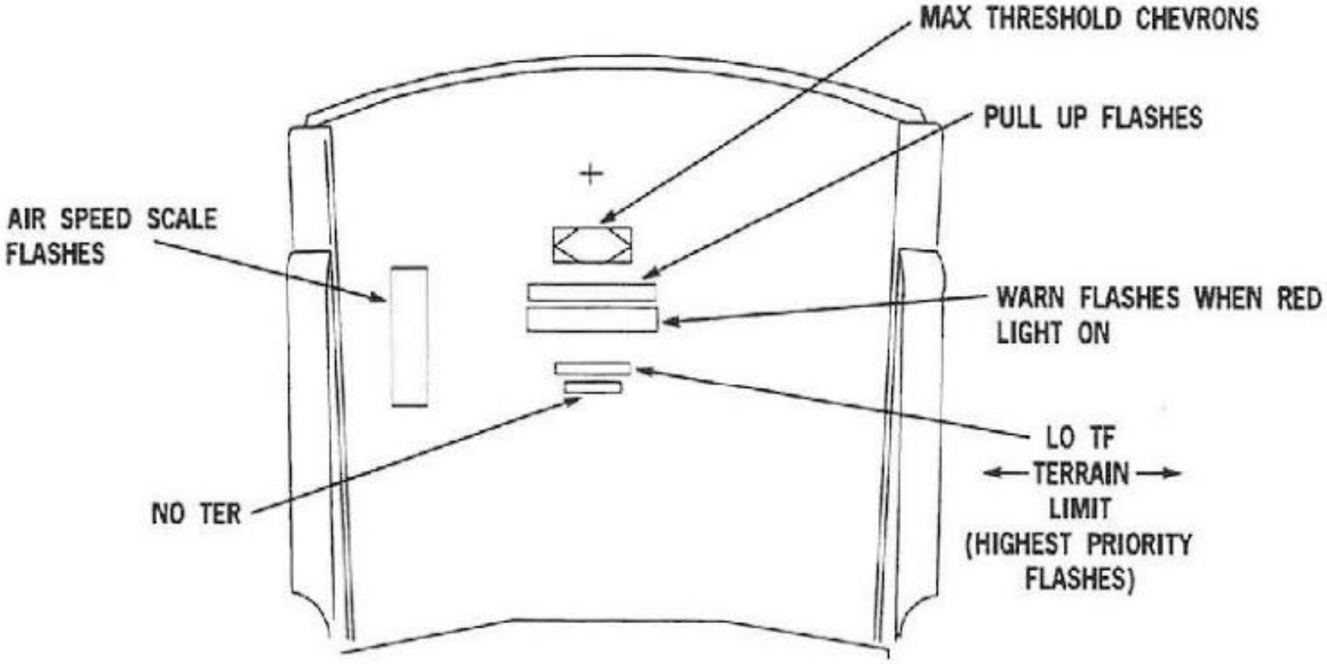


Fig. 2.17. Terrain Following Warnings, Cautions, and Advisories

Conclusion to chapter 2

Main characteristics of the systems:

- Range of detection-10 nm(18.52 km)
- Scan coverage in vertical plane-40 degrees AN/APQ-110, 30 degrees AN/AAQ-13
- Maximum G-limit- up to 4G and -1.5G with selection of preferable overloads with ATF
- RF band-Ku (f-12-18 GHz, λ-2.5-1.6 cm)
- Clearance settings- 100 to 1000 ft

Making a conclusion from the analysis of these systems we can say that the TFR system is well thought out and safe for the crew, as it has a sufficient range of obstacle detection (sufficient for making decisions to avoid collisions), foresees for possible errors of terrain scanning, the procedures of working with the system worked out over decades of use and has algorithms of actions to avoid collisions with the ground and buildings in case of scanning errors.

CHAPTER 3

RADAR CHARACTERISTICS

Now that we know the principle of operation and the main characteristics of the TFR system representatives, we need to understand why the studied systems have these characteristics and how they affect other radar specifications.

Signal-to-Noise Ratio (SNR) will be calculated, while Range and Peak transmit power will be double checked in MATLAB's "Radar Equation Calculator".

First of all, frequency of the radio waves. Modern aircraft radars are using centimetre waves which corresponds to frequencies from 8 GHz to 27 GHz or Super High Frequencies, this is because those higher frequencies have better angular resolution and better angular resolution is needed for understanding amount and types of objects that have been scanned by a radar. With terrain-following radar we scan terrain ahead and bellow of the aircraft's flight path and because terrain mostly consist of different and complex objects, that's TFR is operating on Ku-band(12-18GHz) frequencies that are higher than most aircraft radars (8-12 GHz).

So, the wavelength of Ku-band is 2.5-1.6 cm, for convenience, I chose the frequency 14895 MHz and the wavelength of this frequency is

$$\lambda = \frac{c}{f}\,(\mathrm{m})$$

$$\lambda = \frac{3 \cdot 10^{8}}{14985} = 2\mathrm{cm} = 0.02\ \mathrm{m}$$

Beamwidth of antenna is needed for further calculations and to understand how wide radar beam will be.

$$\Theta = \frac{1.3 * \lambda}{d}$$

Where d is diameter of the antenna, I've selected antenna of the "Буран" weather radar for reference diameter of which is d=0.61 m.

$$\Theta = \frac{1.3 * \lambda}{d} = \frac{1.3 * 0.02}{0.61} \approx 0.0426\ \mathrm{radians} = 2.441\ \mathrm{degrees}$$

Gain of the antenna is a key performance parameter and needed to calculate radars peak power transmit and maximum range

$$G = \frac{4\pi * \eta_A * A}{\lambda^2}$$

Where η_A is antenna efficiency it is value between 0 and 1 but it is rarely below 0.5 and above 0.8, A is antenna area in meters.

$$G = \frac{4\pi * \eta_A * A}{\lambda^2} = \frac{4\pi * 0.75 * 0.29}{0.0004} = 6829.5$$

We also need Gain in decibels for MATLAB calculations

$$G_{dBi} = 10 \ \log_{10} G$$

$$G_{dBi} = 10 \ \log_{10} 6829.5 \approx 38.34389 \text{ dB}$$

To calculate peak, transmit power we will use radar range equation:

$$P_r = \frac{P_t * G^2 * \lambda^2 * \sigma}{(4\pi)^3 * R^4}$$

Where *Pt* is the peak transmitted power in watts. $G^2$is gain for monostatic radar system. λ is the carrier wavelength in meters. σ is the mean RCS of the target in square meters, which in our case I chose to be 10 square meter. R is the range from the radar to the target in meters.

Since the maximum distance of radar signal detection depends on the minimum power of the detected signal, the basic radar equation can be written as follows:

$$R_{max}^4 = \frac{P_t * G^2 * \lambda^2 * \sigma}{(4\pi)^3 * P_{\min r}}$$

Where $P_{\min r}$ is minimum receivable power which for modern radars is 10^{-12} watts. TFR systems that were analysed had maximum range of 18.52 km, but because civilian aircrafts are mostly inferior in terms of maneuverability than military fighter or attack aircrafts I suggest that maximum range must be 20 km at very least.

With that in mind peak power transmit power equation looks like this

$$P_t = \frac{R^4 * (4\pi)^3 * P_{\min r}}{G^2 * \lambda^2 * \sigma}$$

$$P_t = \frac{20000^4 * (4\pi)^3 * 10 * 10^{-12}}{6829.5^2 * 0.02^2 * 10} = 16992 \text{ watts}$$

That means peak transmit power to detect an object with RCS of 10 square meters at range of 20 km is 16.99 kW, but our main objects to detect are trees, buildings and terrain RCS of which is much bigger and therefore easier to detect and less power needed. For example, RCS of an automobile is 100 square meters and to detect it we need 1.7 kW of power.

To calculate pulse width, I will use resolution equation

$$\Delta R = \frac{c\tau}{2}$$

Where ΔR called the range resolution of the radar. Two targets spaced by more than ΔR will be resolved in range; targets spaced by less than ΔR will not. τ is pulse width.

A pulse width of 1 μs results in a range resolution of (3×10^8)(10^{-6})/2 = 150 m. But objects could be a lot closer than 150 meters. 15 meters is more realistic distance between closely positioned objects

Our equation to find pulse width looks like this

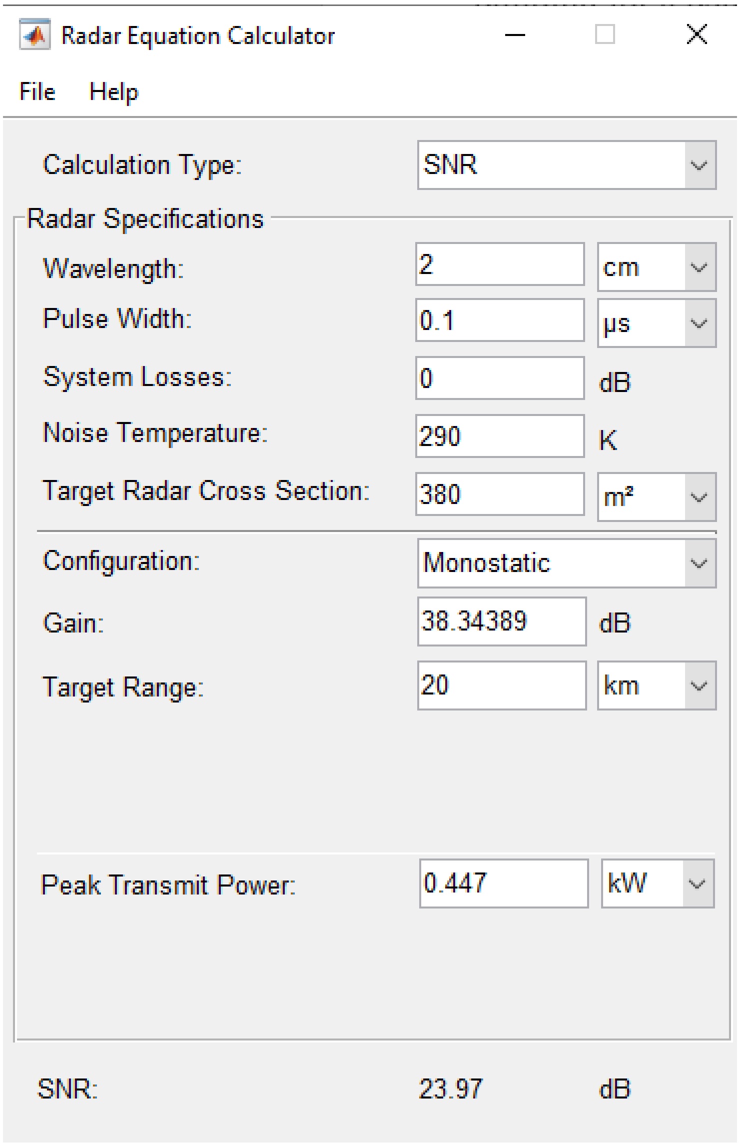
$$\tau = \frac{\Delta R * 2}{c} = \frac{15 * 2}{3 \cdot 10^8} = 0.0000001 = 10^{-7}\text{second}$$

With all of that in mind we need to calculate SNR using MATLAB's "Radar Equation Calculator".

The only variable that I will change is RCS, I will put an RCS of a side of my building for a better representation. For that matter I will also recalculate peak power transmit. Dimensions of the side of my building are next 11 meters wide, 24.3 meters high or 267.3 square meters. For RCS it will be 380 square meters.

$$P_t = \frac{20000^4 * (4\pi)^3 * 10 * 10^{-12}}{6829.5^2 * 0.02^2 * 380} = 447 \text{ watts}$$

This is SNR ratio for RCS of 380 square meters



Calculation Type: SNR

Radar Specifications

Wavelength: 2 cm

Pulse Width: 0.1 μs

System Losses: 0 dB

Noise Temperature: 290 K

Target Radar Cross Section: 380 m²

Configuration: Monostatic

Gain: 38.34389 dB

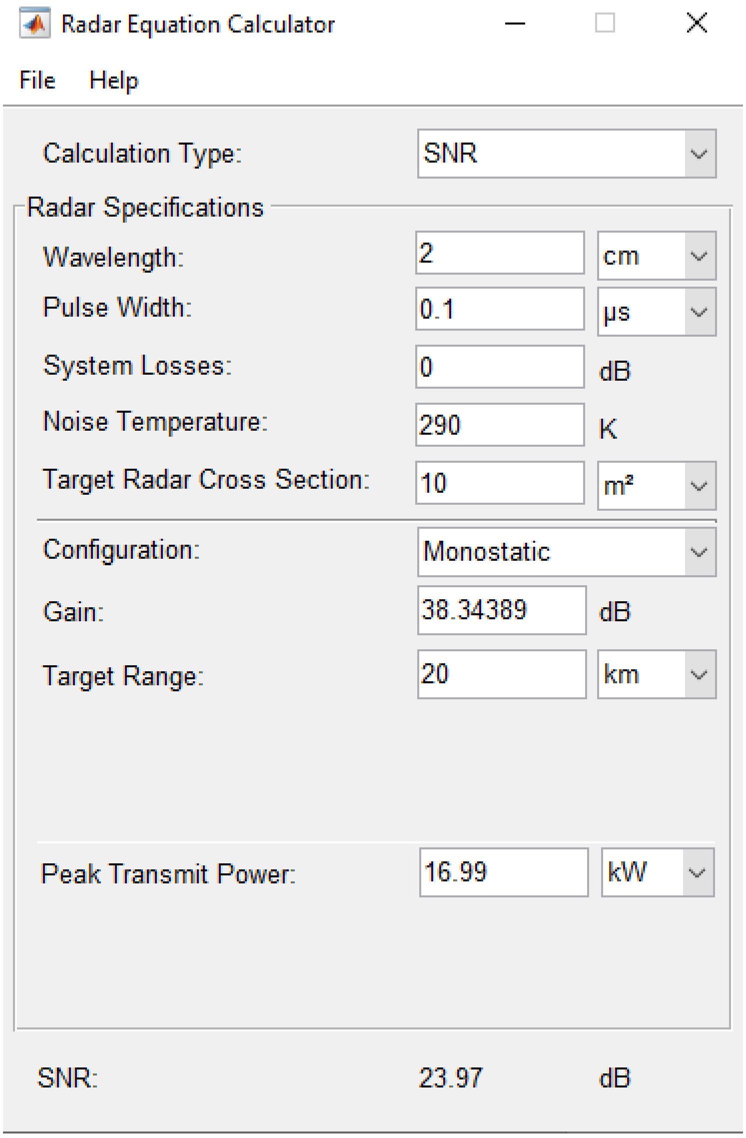
Target Range: 20 km

Peak Transmit Power: 0.447 kW

SNR: 23.97 dB

Fig. 3.1. SNR with RCS of 380 m^2

And this is SNR ratio for RCS of 10 square meters



Calculation Type: SNR

Radar Specifications

Wavelength: 2 cm

Pulse Width: 0.1 μs

System Losses: 0 dB

Noise Temperature: 290 K

Target Radar Cross Section: 10 m²

Configuration: Monostatic

Gain: 38.34389 dB

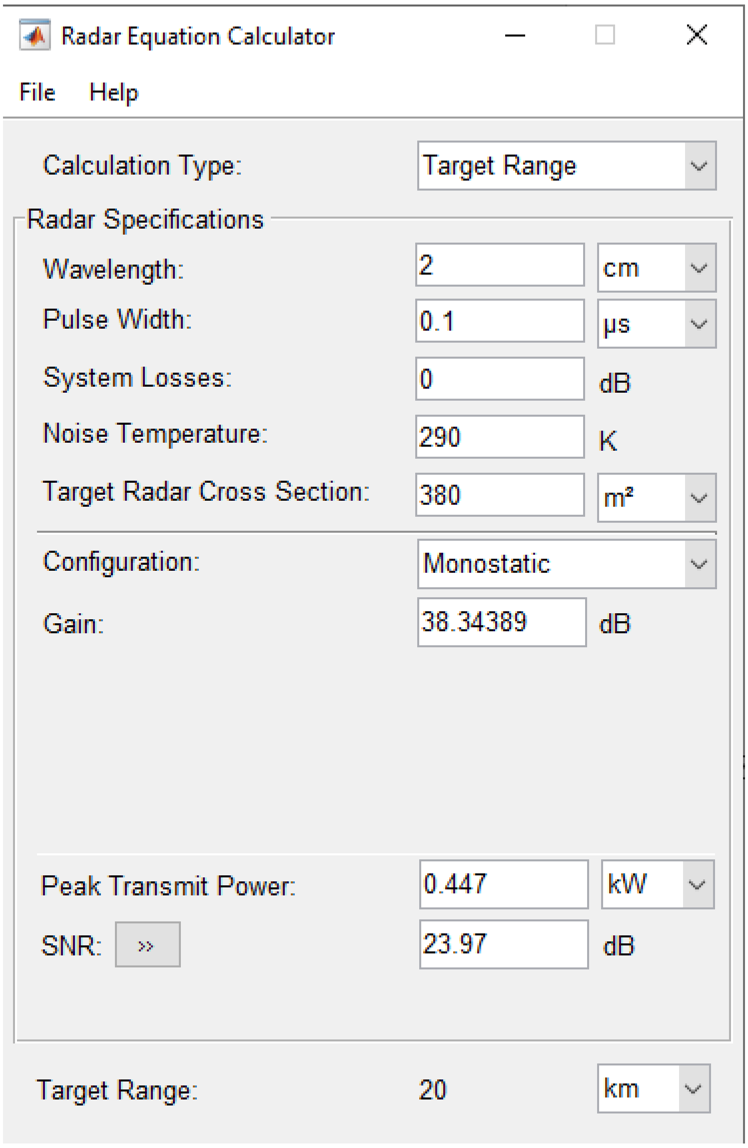
Target Range: 20 km

Peak Transmit Power: 16.99 kW

SNR: 23.97 dB

Fig. 3.2. SNR with RCS of 10 m^2

With SNR value in mind lets double check range and peak transmit power of RCS of 380 m^2.



Calculation Type: Target Range

Radar Specifications

Wavelength: 2 cm

Pulse Width: 0.1 μs

System Losses: 0 dB

Noise Temperature: 290 K

Target Radar Cross Section: 380 m²

Configuration: Monostatic

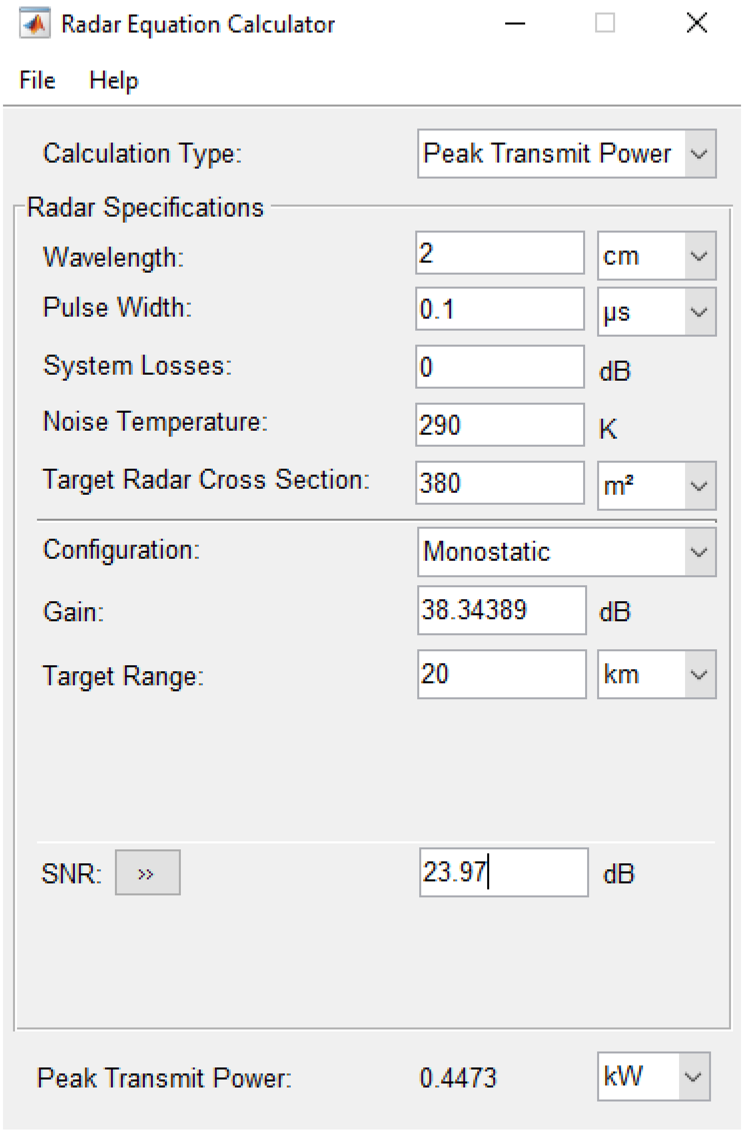
Gain: 38.34389 dB

Peak Transmit Power: 0.447 kW

SNR: 23.97 dB

Target Range: 20 km

Fig. 3.3. Range with RCS of 380 m^2



Calculation Type: Peak Transmit Power

Wavelength: 2 cm

Pulse Width: 0.1 µs

System Losses: 0 dB

Noise Temperature: 290 K

Target Radar Cross Section: 380 m²

Configuration: Monostatic

Gain: 38.34389 dB

Target Range: 20 km

SNR: 23.97 dB

Peak Transmit Power: 0.4473 kW

Fig. 3.4. Peak transmit power with RCS of 380 m^2

Also, I would like to make calculations to LANTIRN size TFR.

So, for LANTRIN sized system d=0.305 m and antenna area A=0.073 m^2

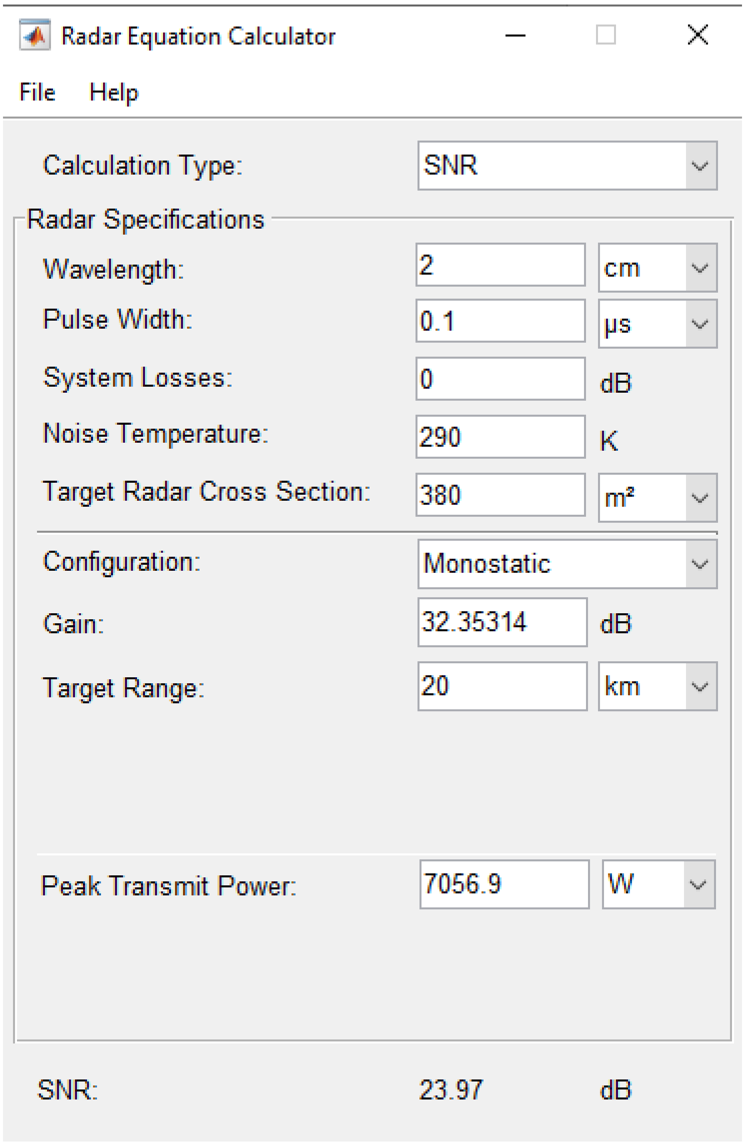
$$\Theta = \frac{1.3 * \lambda}{d} = \frac{1.3 * 0.02}{0.305} \approx 0.085 \text{ radians} = 4.87 \text{ degrees}$$

$$G = \frac{4\pi * \eta_A * A}{\lambda^2} = \frac{4\pi * 0.75 * 0.073}{0.0004} = 1719.15$$

$$G_{dBi} = 10 \ \log_{10} 1719.15 \approx 32.35314 \text{ dB}$$

I will take RCS value of 380 m^2

$$P_t = \frac{20000^4 * (4\pi)^3 * 10 * 10^{-12}}{1719.15^2 * 0.02^2 * 10} = 7056.9 \text{ watts}$$



Calculation Type: SNR

Radar Specifications

Wavelength: 2 cm

Pulse Width: 0.1 μs

System Losses: 0 dB

Noise Temperature: 290 K

Target Radar Cross Section: 380 m²

Configuration: Monostatic

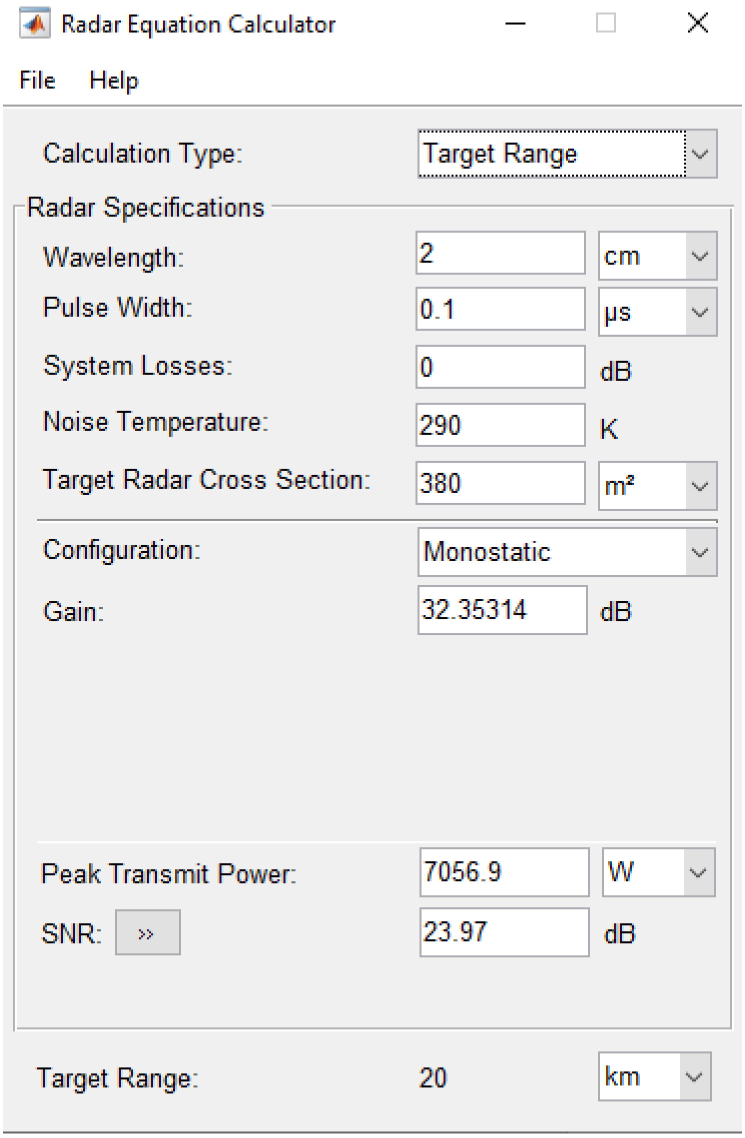
Gain: 32.35314 dB

Target Range: 20 km

Peak Transmit Power: 7056.9 W

SNR: 23.97 dB

Fig. 3.5. SNR of LANTIRN sized system



Calculation Type: Target Range

Wavelength: 2 cm

Pulse Width: 0.1 μs

System Losses: 0 dB

Noise Temperature: 290 K

Target Radar Cross Section: 380 m^2

Configuration: Monostatic

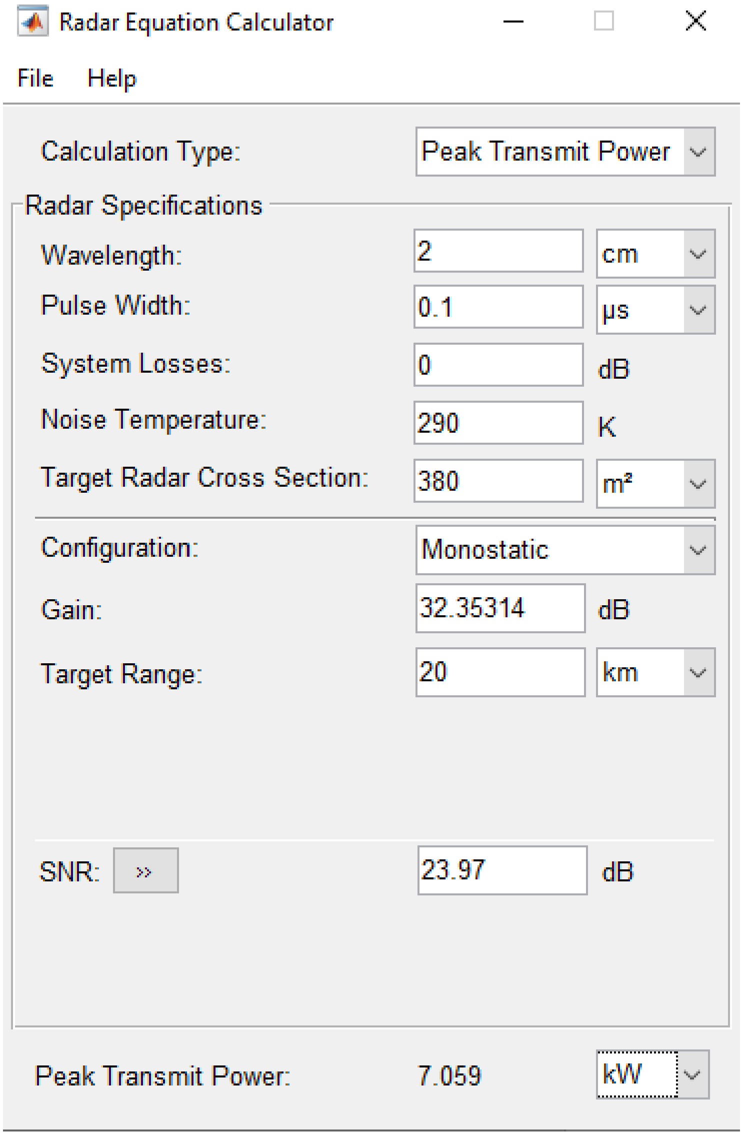
Gain: 32.35314 dB

Peak Transmit Power: 7056.9 W

SNR: 23.97 dB

Target Range: 20 km

Fig. 3.6. Range of LANTIRN sized system



Calculation Type: Peak Transmit Power

Radar Specifications

Wavelength: 2 cm

Pulse Width: 0.1 μs

System Losses: 0 dB

Noise Temperature: 290 K

Target Radar Cross Section: 380 m²

Configuration: Monostatic

Gain: 32.35314 dB

Target Range: 20 km

SNR: >> 23.97 dB

Peak Transmit Power: 7.059 kW

Fig. 3.7. Peak transmit power of LANTIRN sized system

Conclusion to chapter 3

In conclusion to this chapter, range the system can be increased but power characteristics will change due to increase in range also power characteristics will change if dimensions of the system will change. Most importantly not all of the current radar systems will be capable of integration with TFR systems. Which leads to two possible ways of implementation of the TFR system first is to implement TF computer to a radar capable of TF or to adaptation of LANTRIN like pods. There is also a third way, much more costly but with its own benefits, installation of AESA(active electronically scanned array) radar system which allows to use different frequencies and scanning patterns. There already is aircraft with AESA radar that capable of TFR, Dassault Rafale. It is a matter of time when AESA radars or similar in capabilities radar systems will be installed in civilian aircraft on a mass scale.

CONCLUSION

In conclusion, I’ve managed to increase range of the system, by calculating method, to 20 kilometres with peak power transmit of 447 watts on the target with RCS of 380 square meters with antenna diameter of 61 centimetre and similar results with antenna diameter of 30.5 centimetres but with higher peak power transmit of 7059 watts.

The TFR system has the potential to become an essential part of future aircraft, both because of its usefulness in low visibility and varying terrain, and for aircraft controlled partially or fully by artificial intelligence as a tool for scanning terrain to make further decisions. By implementing the system, it will allow pilots workload to decrease and increase efficiency on low altitudes by automating process of such flight. The system is not limited in size and can also be integrated into existing aircraft and radar systems. It is a useful tool with wide scenarios of use, from ground mapping to flights in varying terrain such as mountains.

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